Understanding the Earth's energy budget and implications for future warming

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energy balance equation

$$R = F + \lambda \Delta T$$

energy balance equation

$$R = F + \lambda \Delta T$$

forcing

energy balance equation

$$R = F + \lambda \Delta T$$

response

forcing

energy balance equation

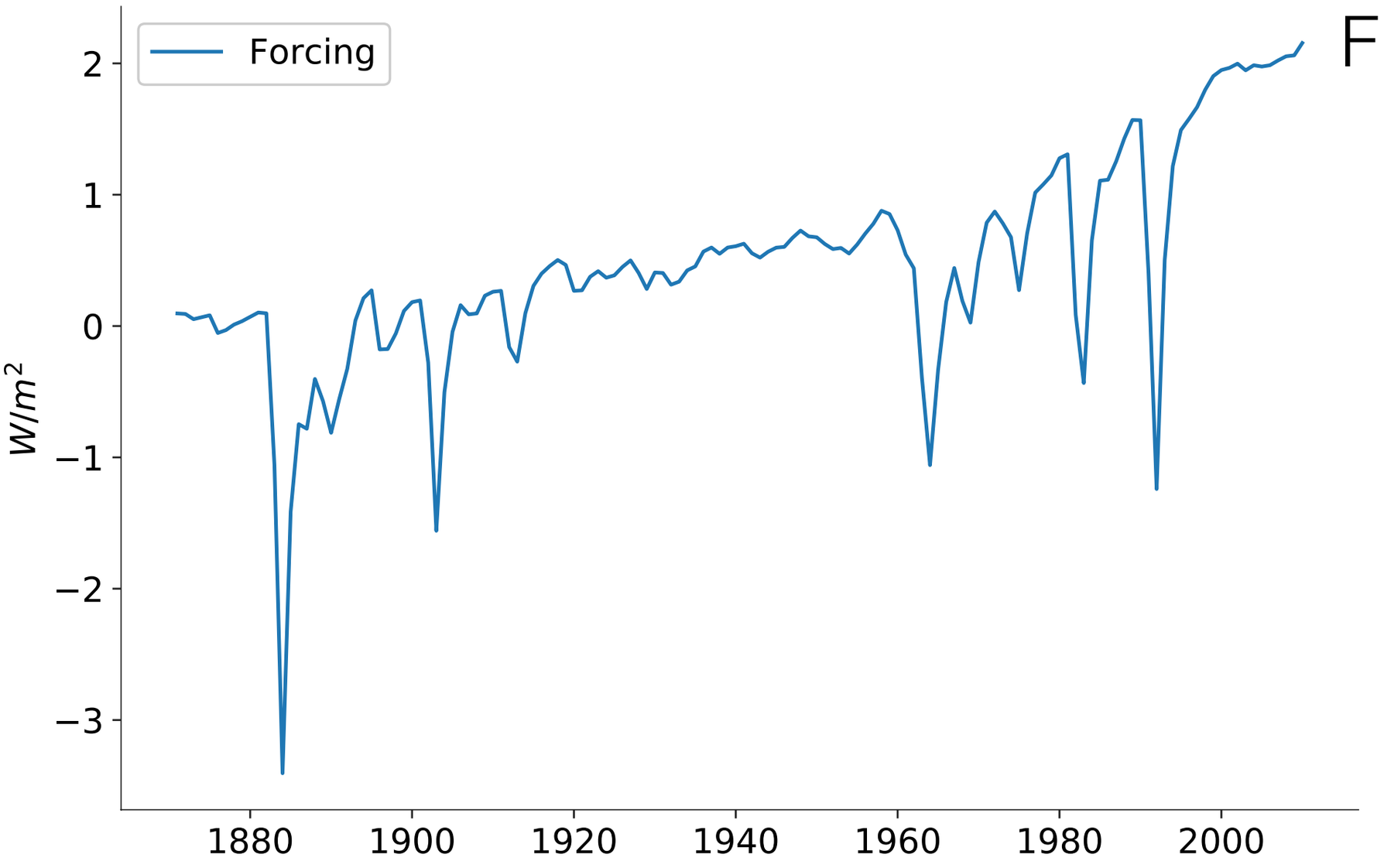
$$R = F + \lambda \Delta T$$

TOA net flux
EEI

forcing

response

$$R = F + \lambda \Delta T$$



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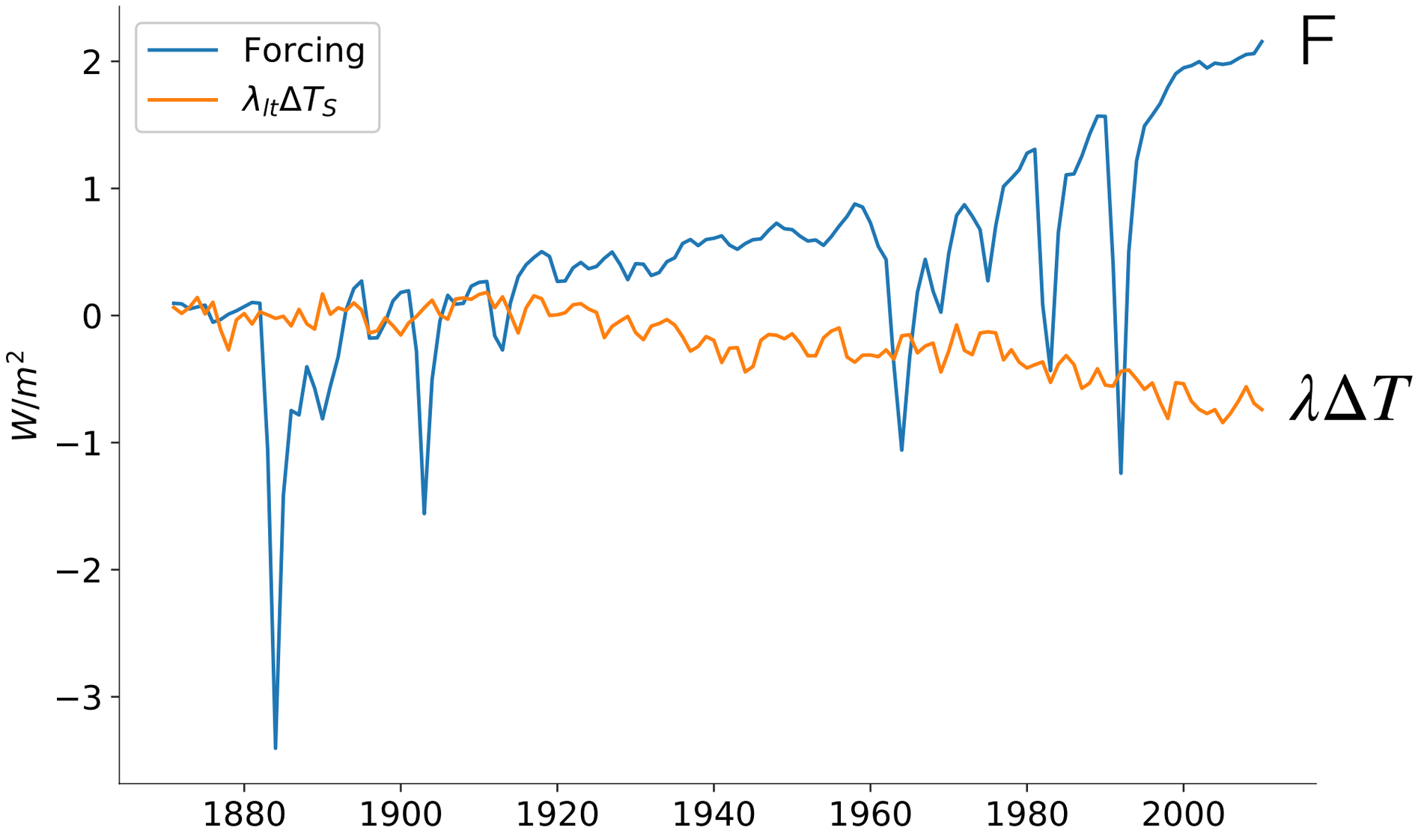

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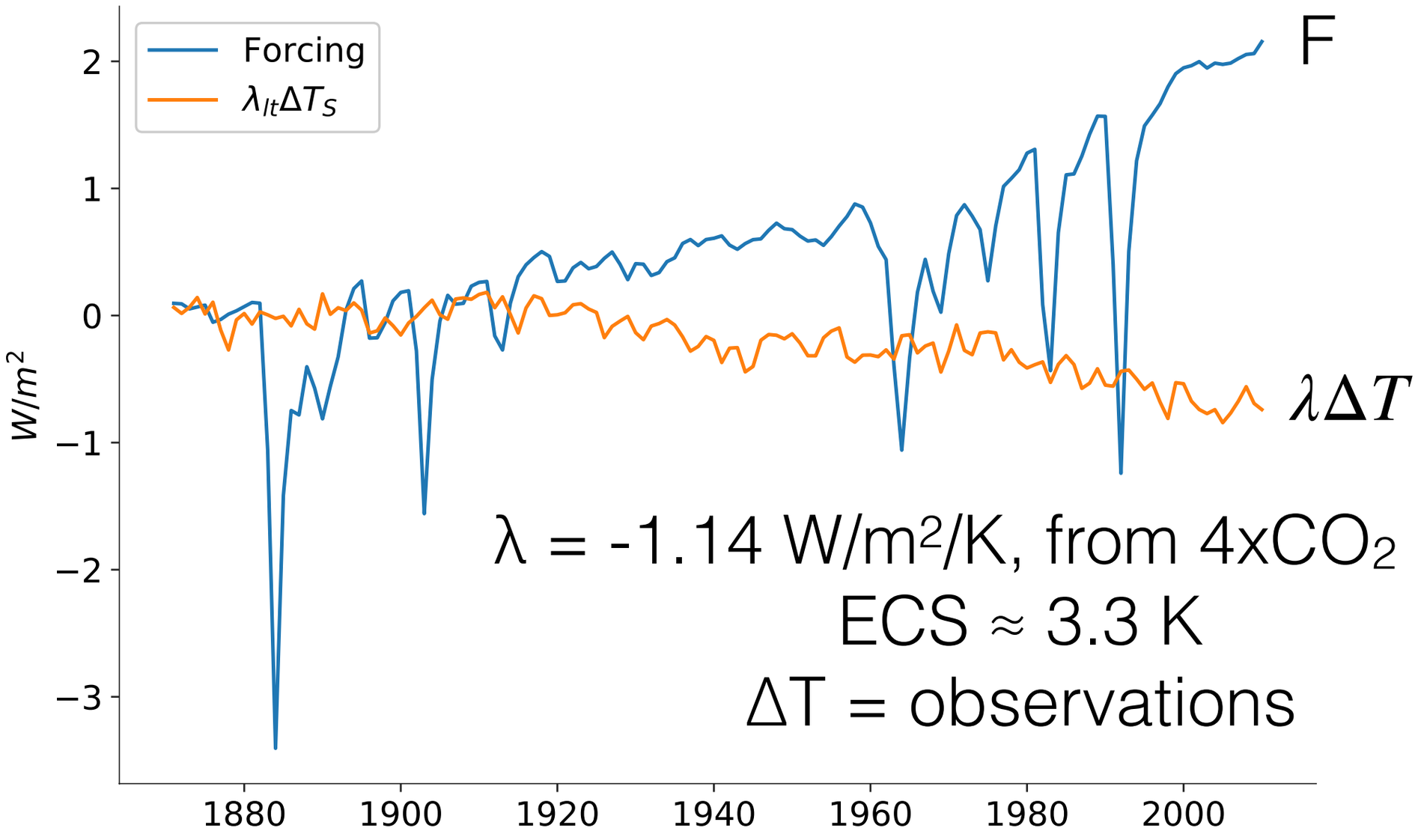

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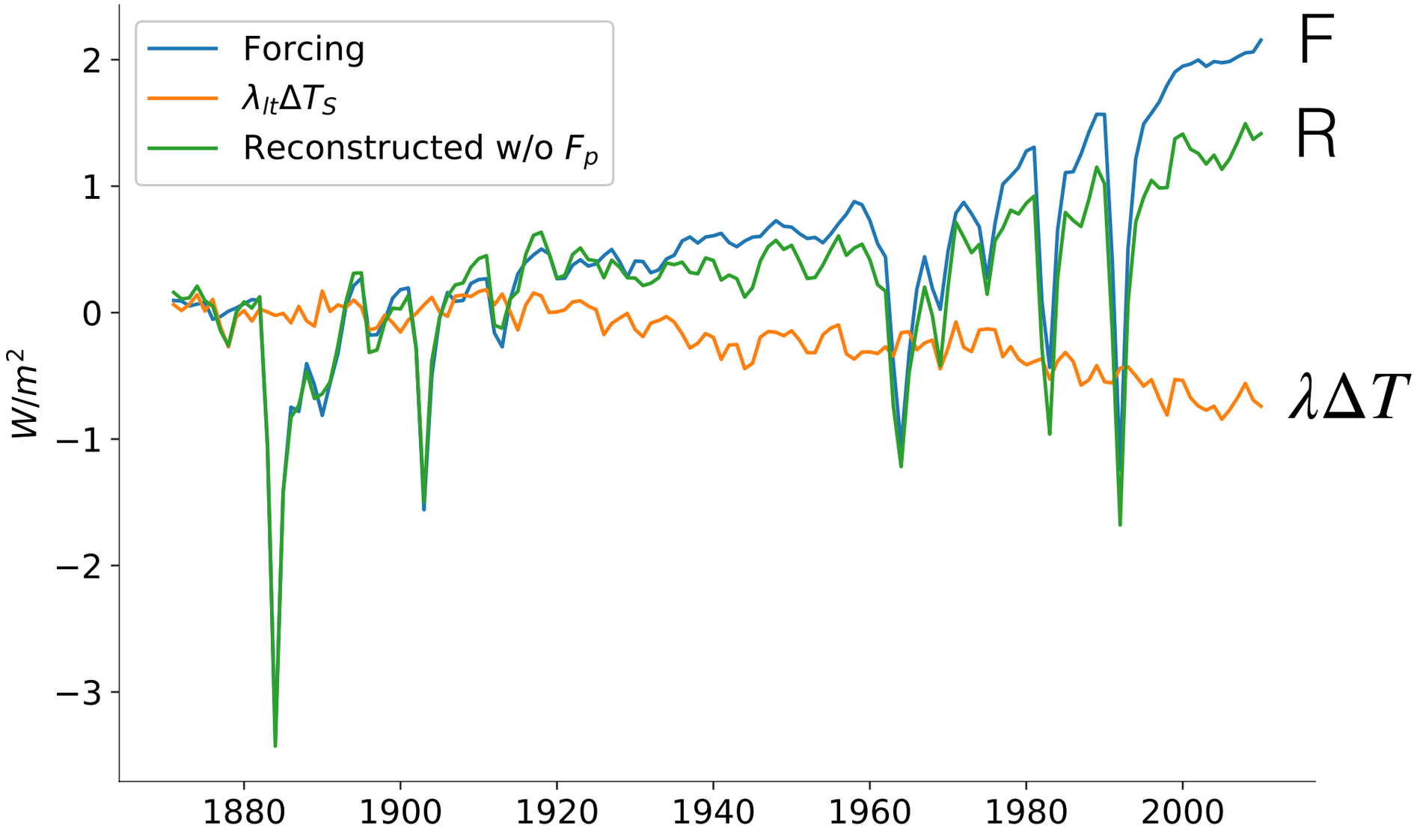
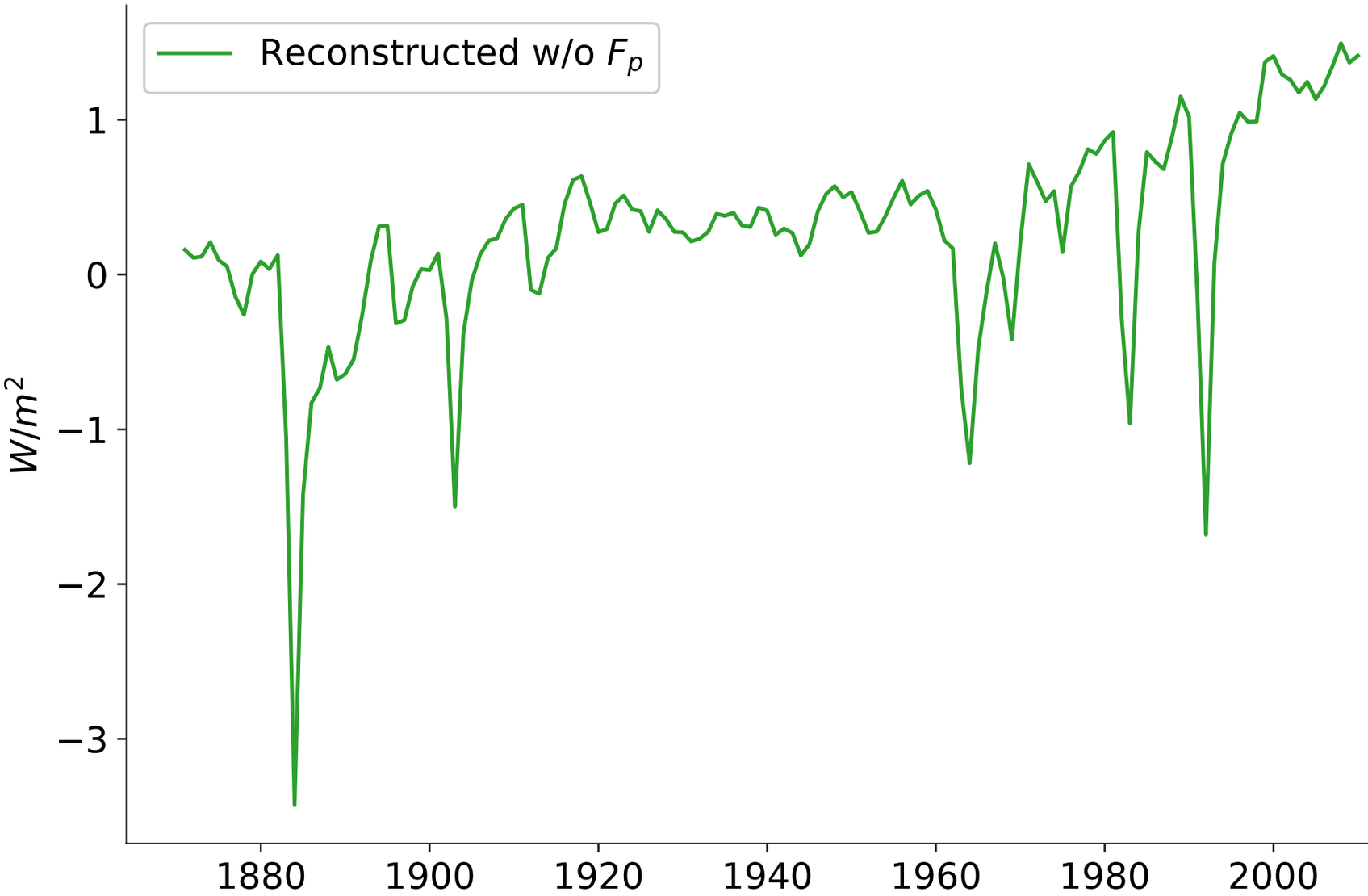


$$\boxed{R} = F + \lambda \Delta T$$



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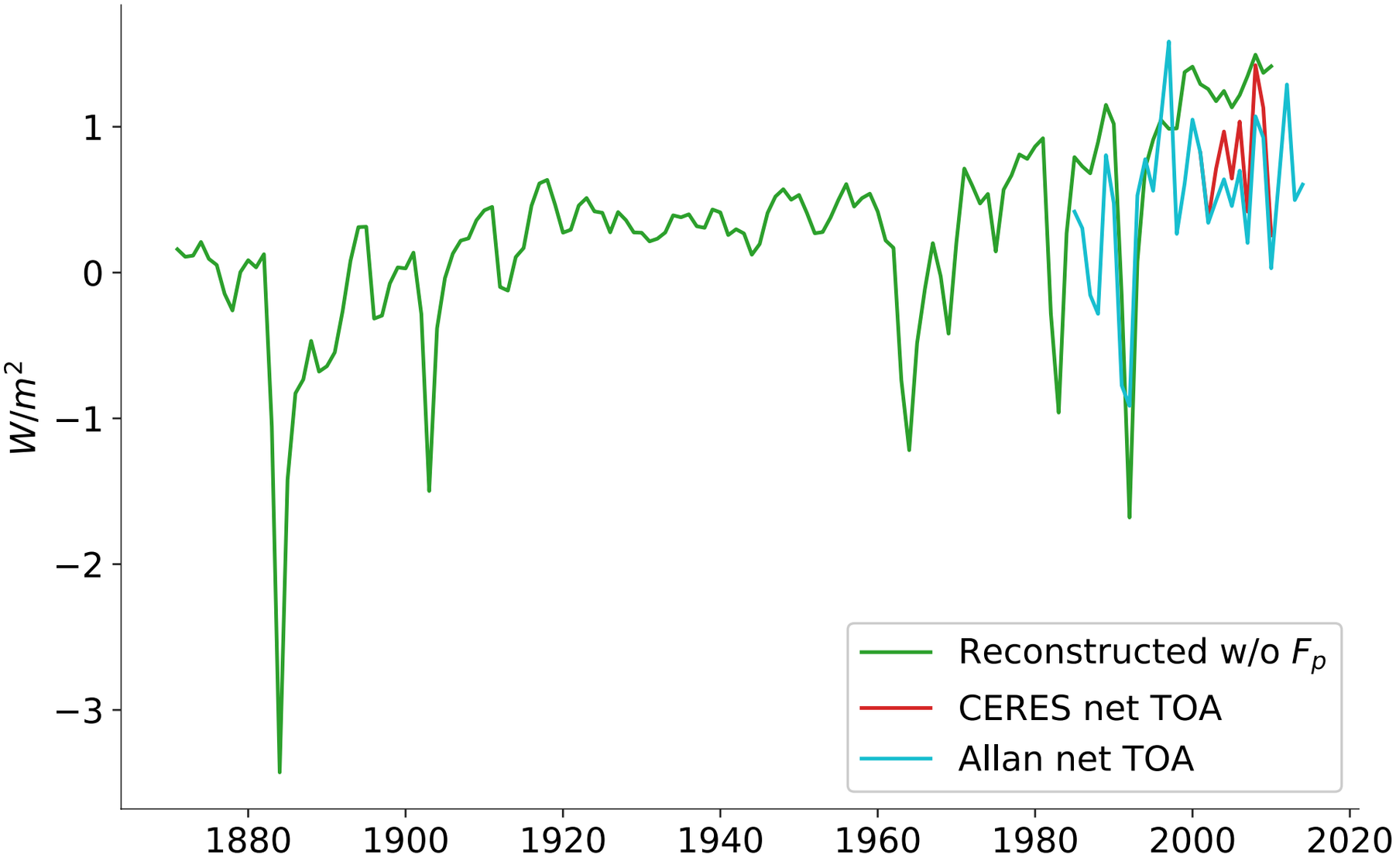

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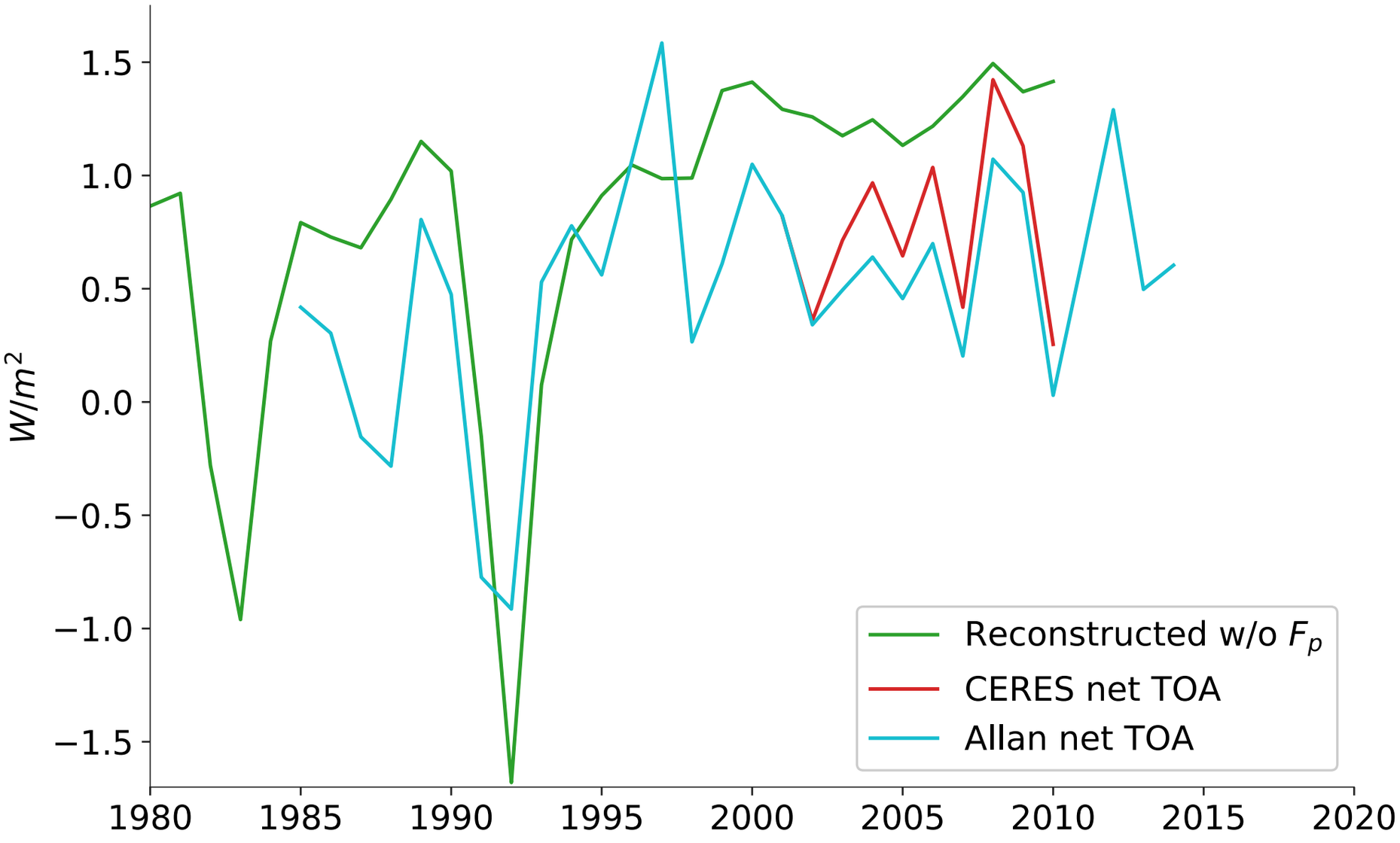

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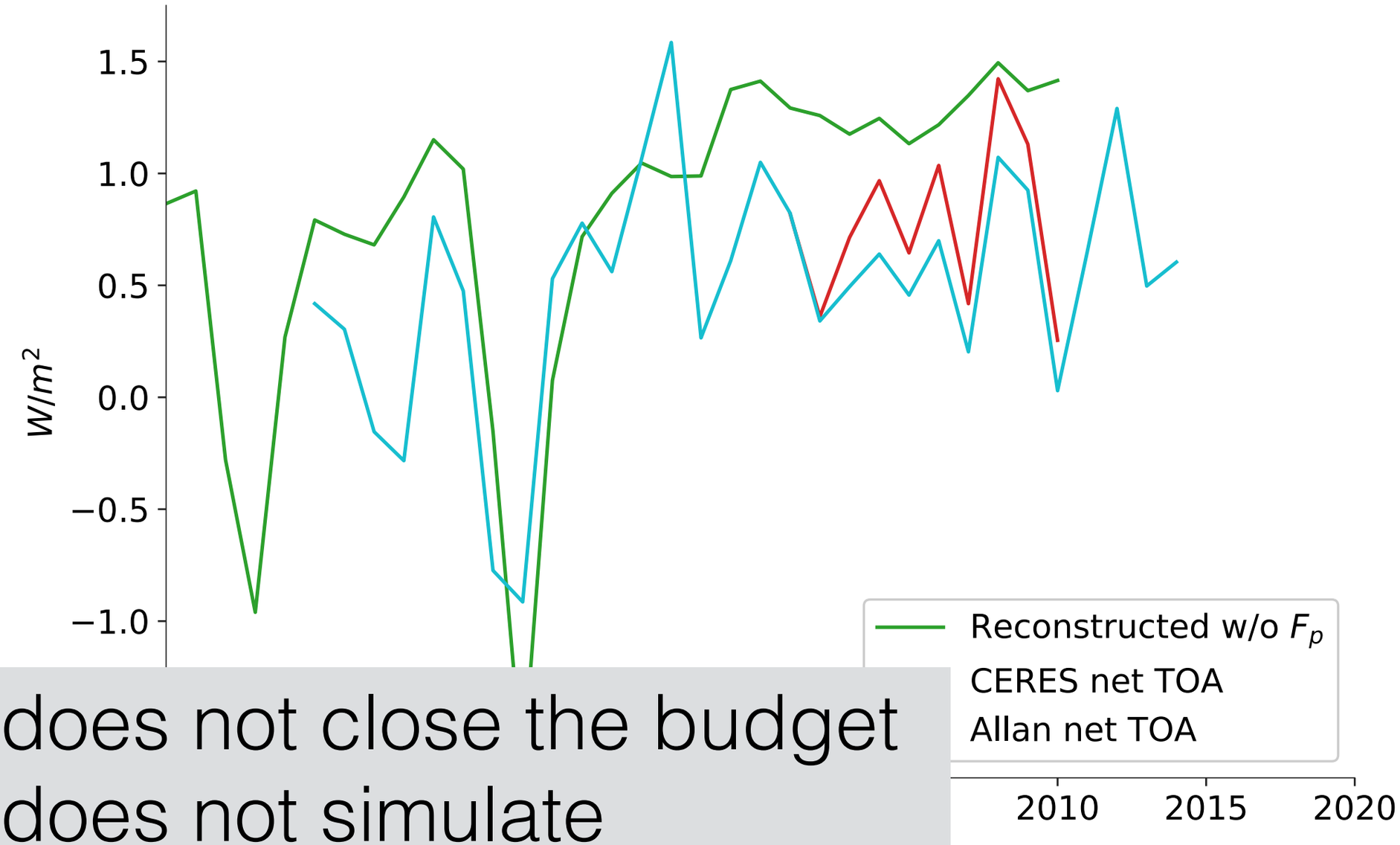
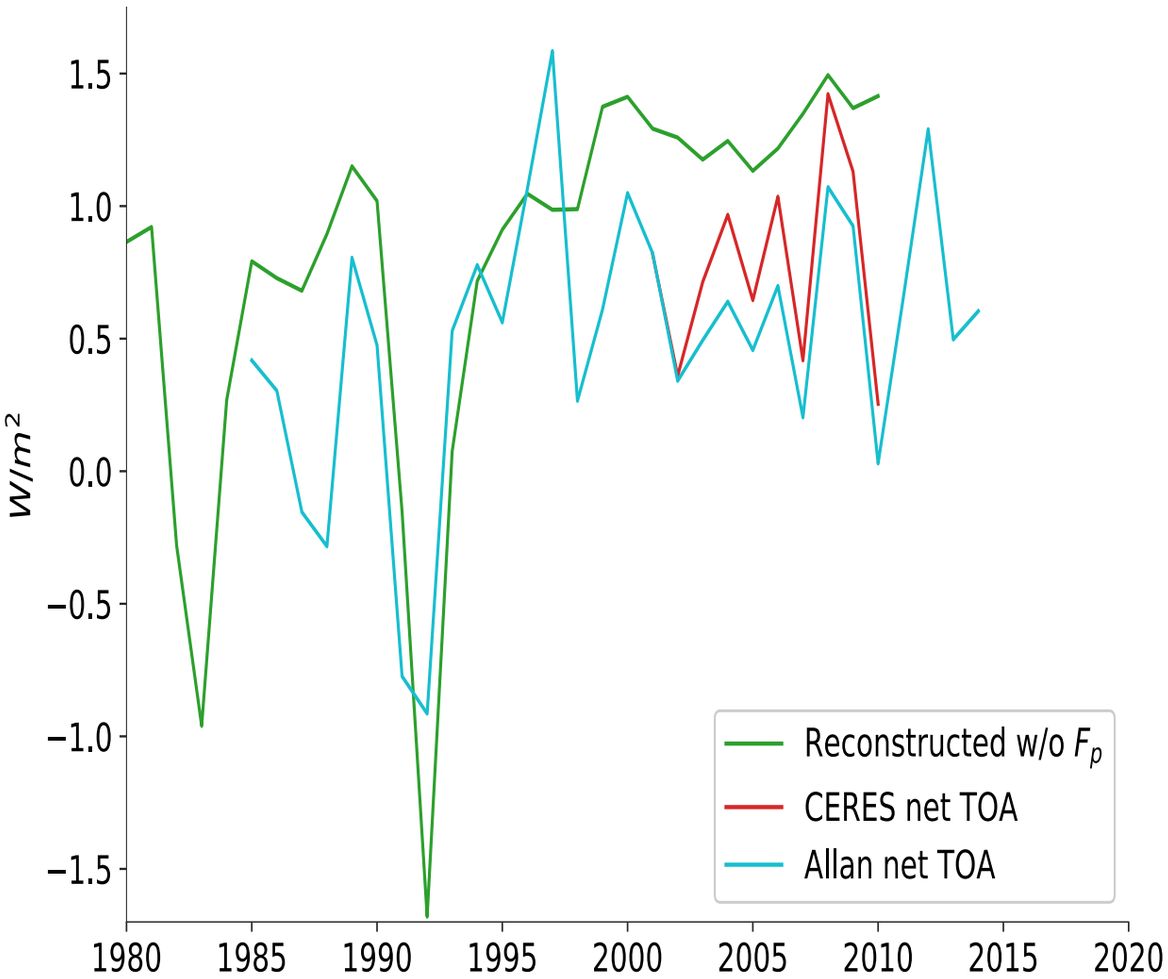


- does not close the budget
- does not simulate interannual variability

$$\boxed{R} = F + \lambda \Delta T$$



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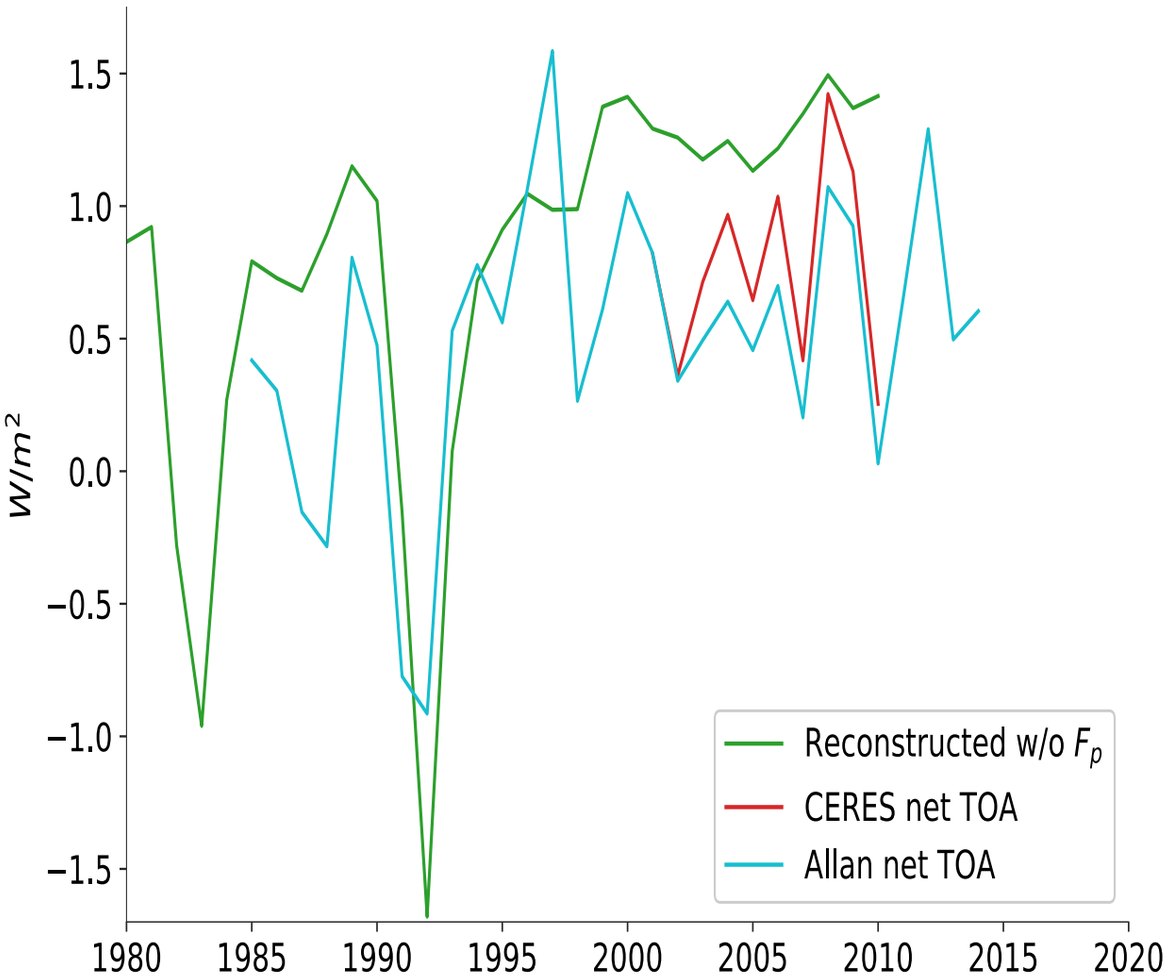
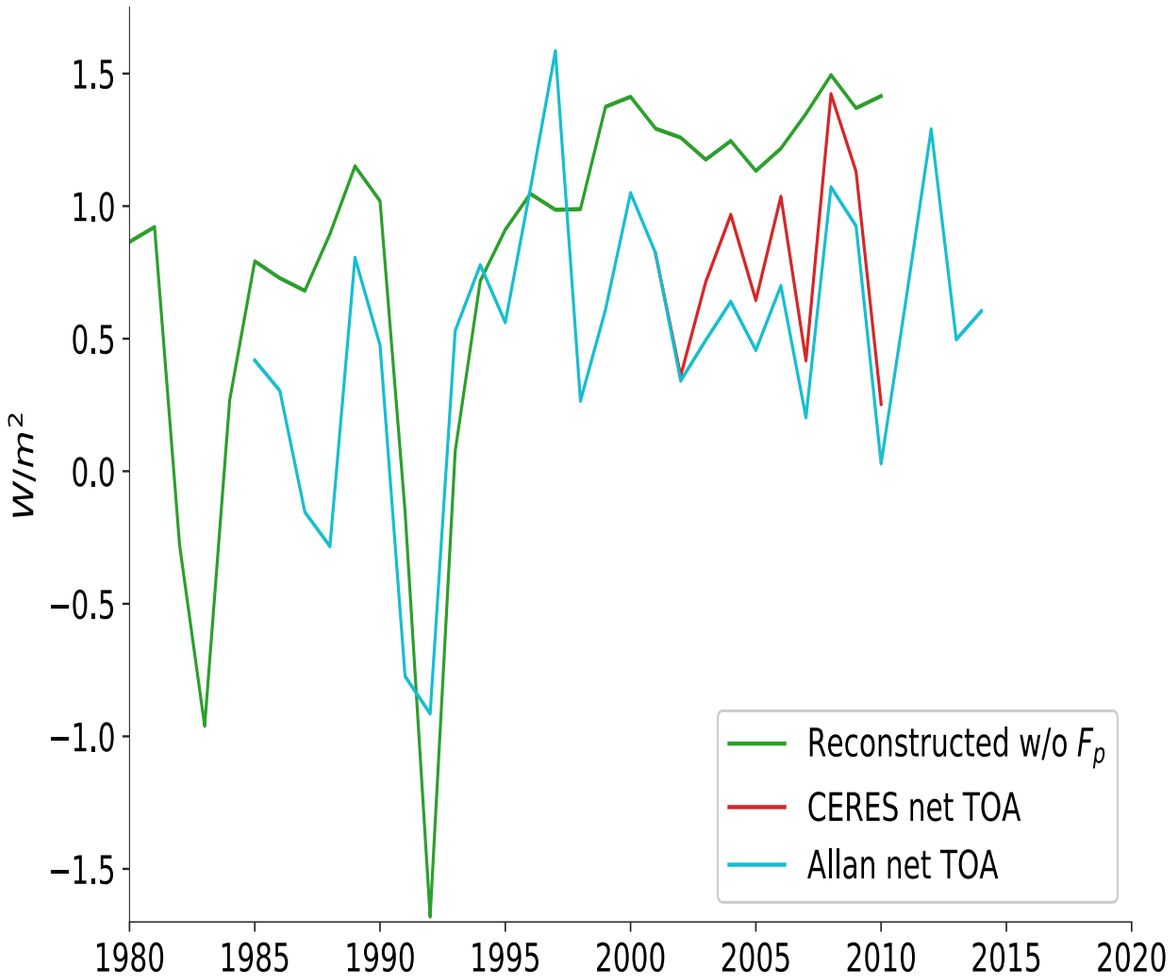


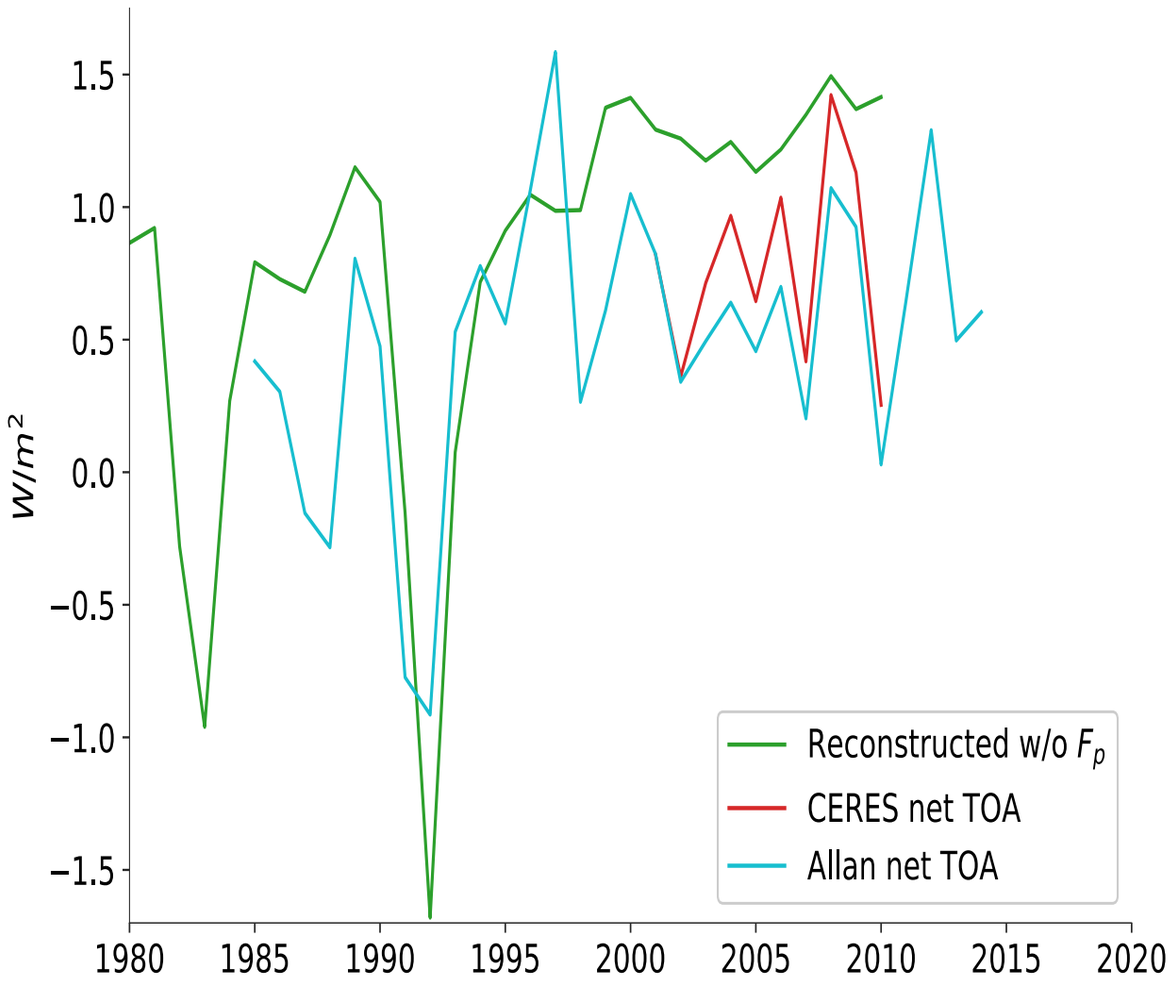
- obs. *R* is wrong

$$\boxed{R} = F + \lambda \Delta T$$



- obs. *R* is wrong
- *F* is wrong

$$\boxed{R} = F + \lambda \Delta T$$



- obs. R is wrong
- F is wrong
- λ is wrong

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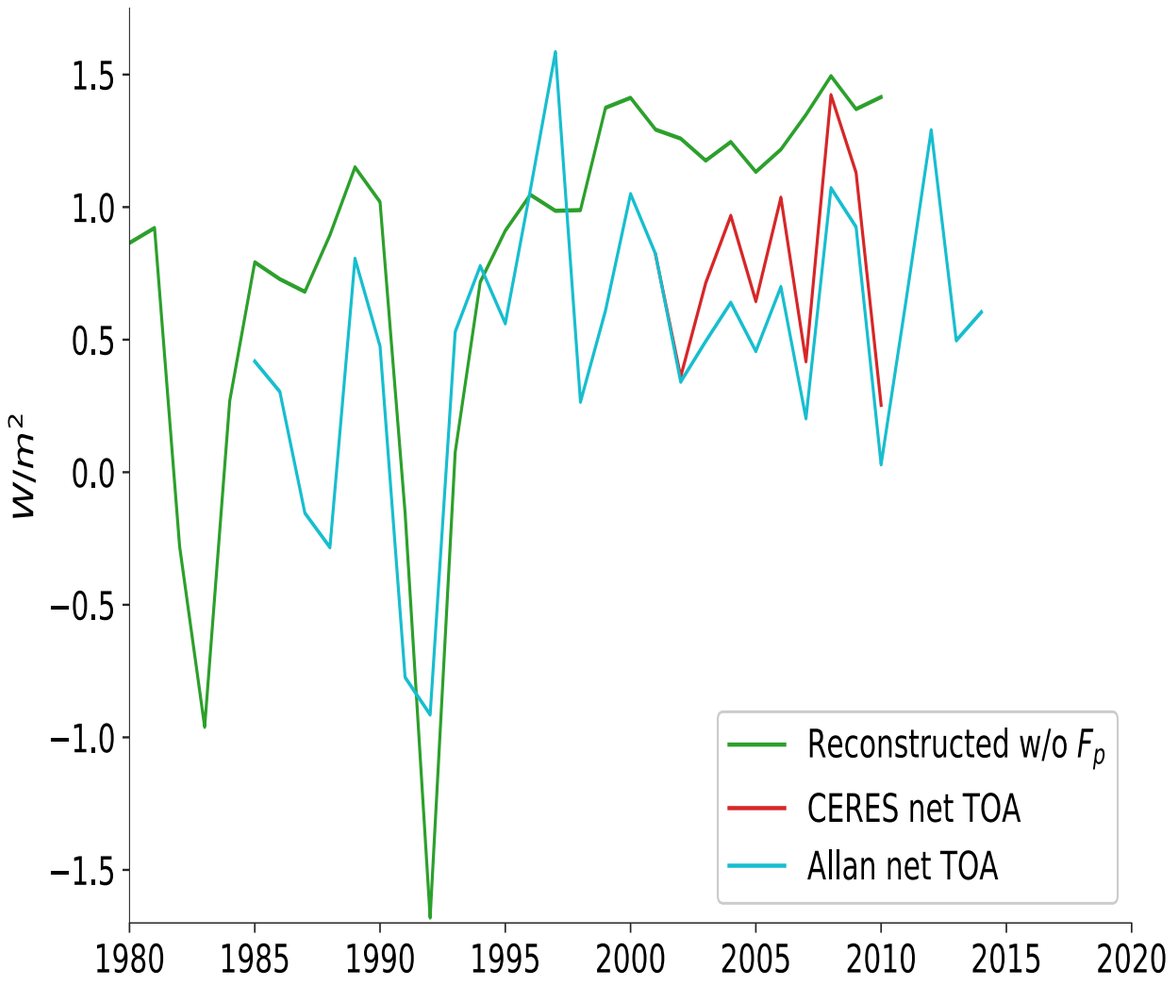

- obs. R is wrong
- F is wrong
- λ is wrong
- $R = F + \lambda \Delta T$ is wrong

energy balance equation

$$R = F + \lambda \Delta T + F_P$$

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TOA net flux
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$$R = F + \lambda \Delta T + F_P$$

TOA net flux
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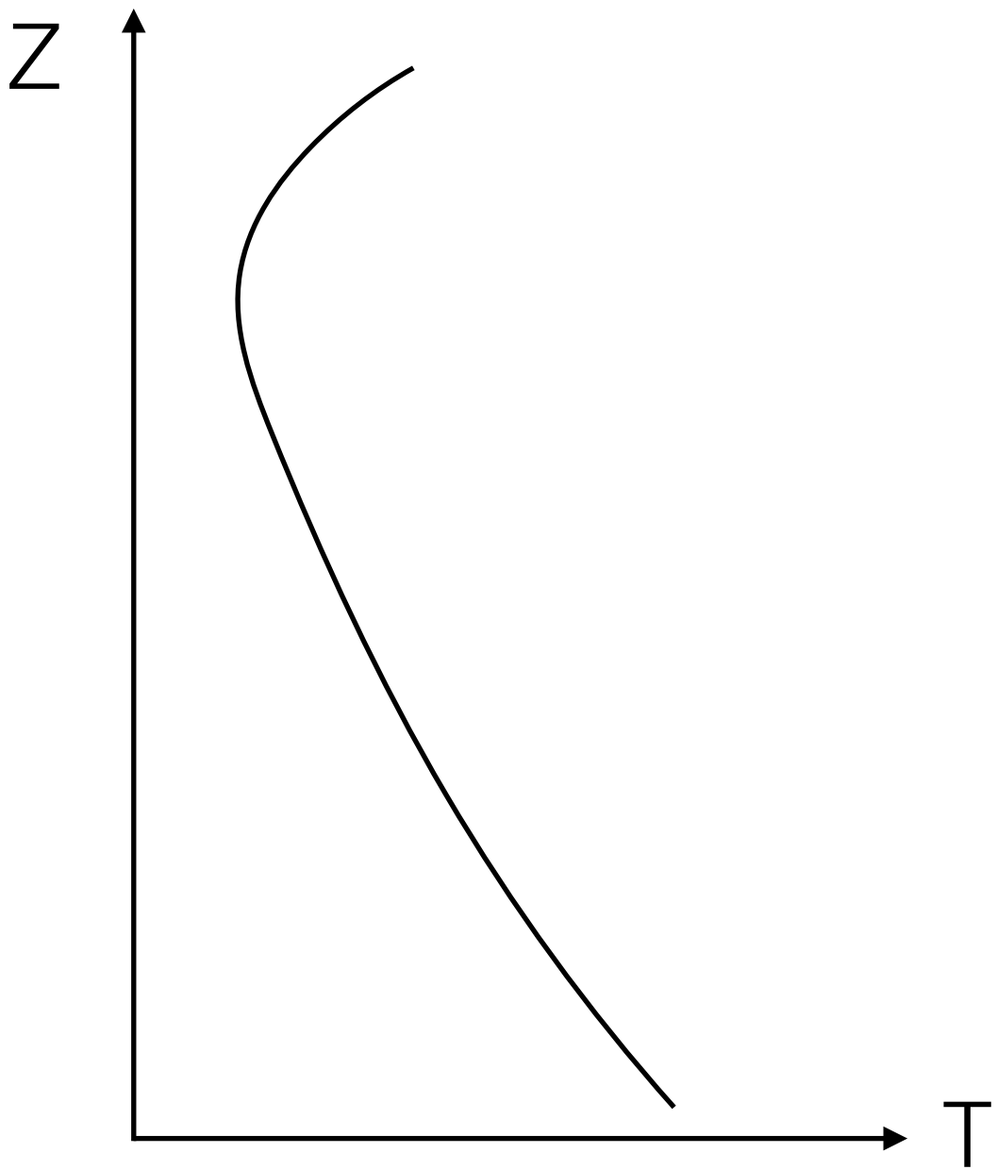
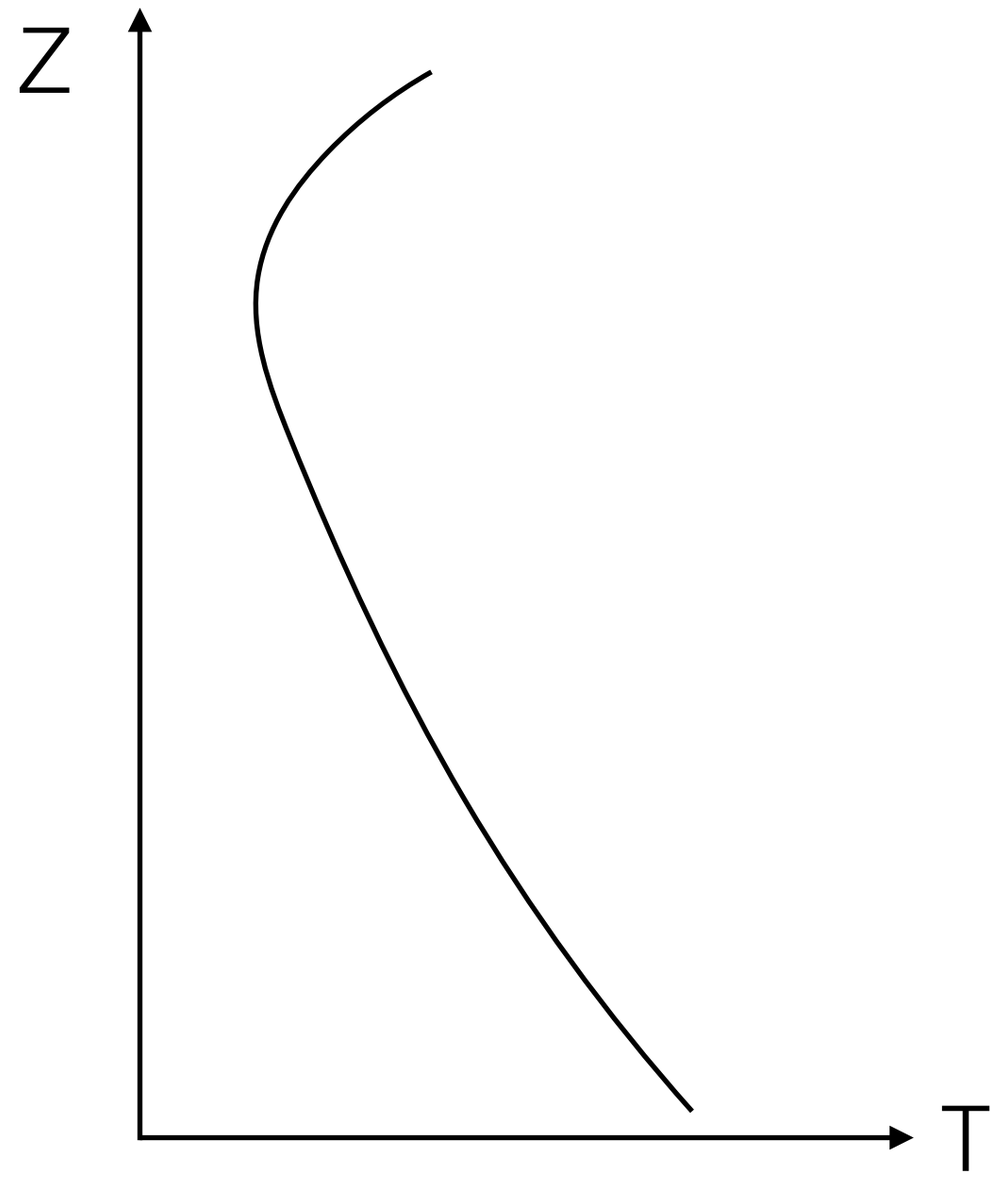
TOA net flux *R* is not just a function of global average T, but also of the pattern of warming

West Pacific

East Pacific

Zhou et al..: Analyzing the dependence of global cloud feedback on the spatial pattern of sea surface temperature change with a Green's function approach, Journal of Advances in Modeling Earth Systems, 9, 2174-2189, 10.1002/2017MS001096, 2017.





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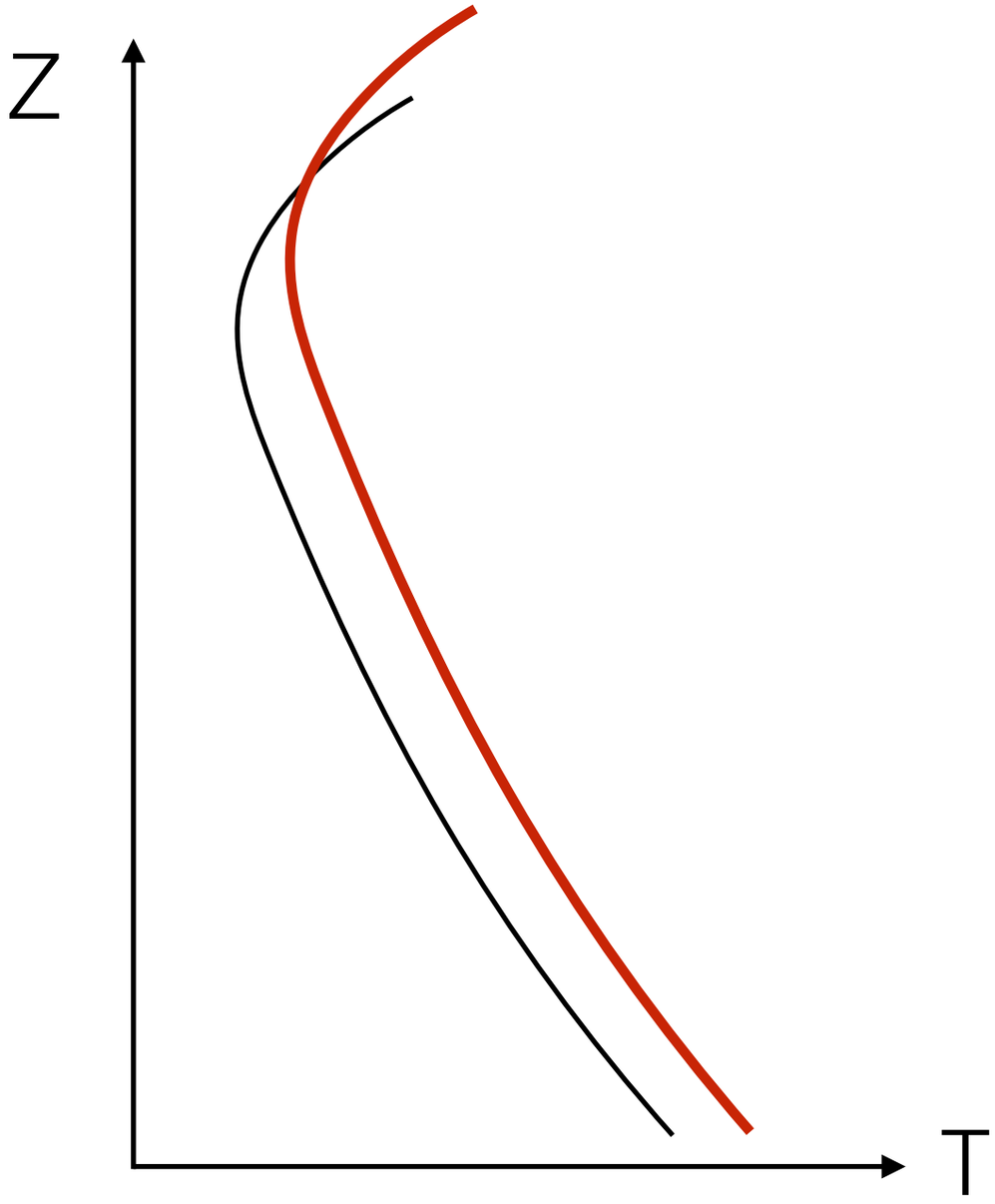

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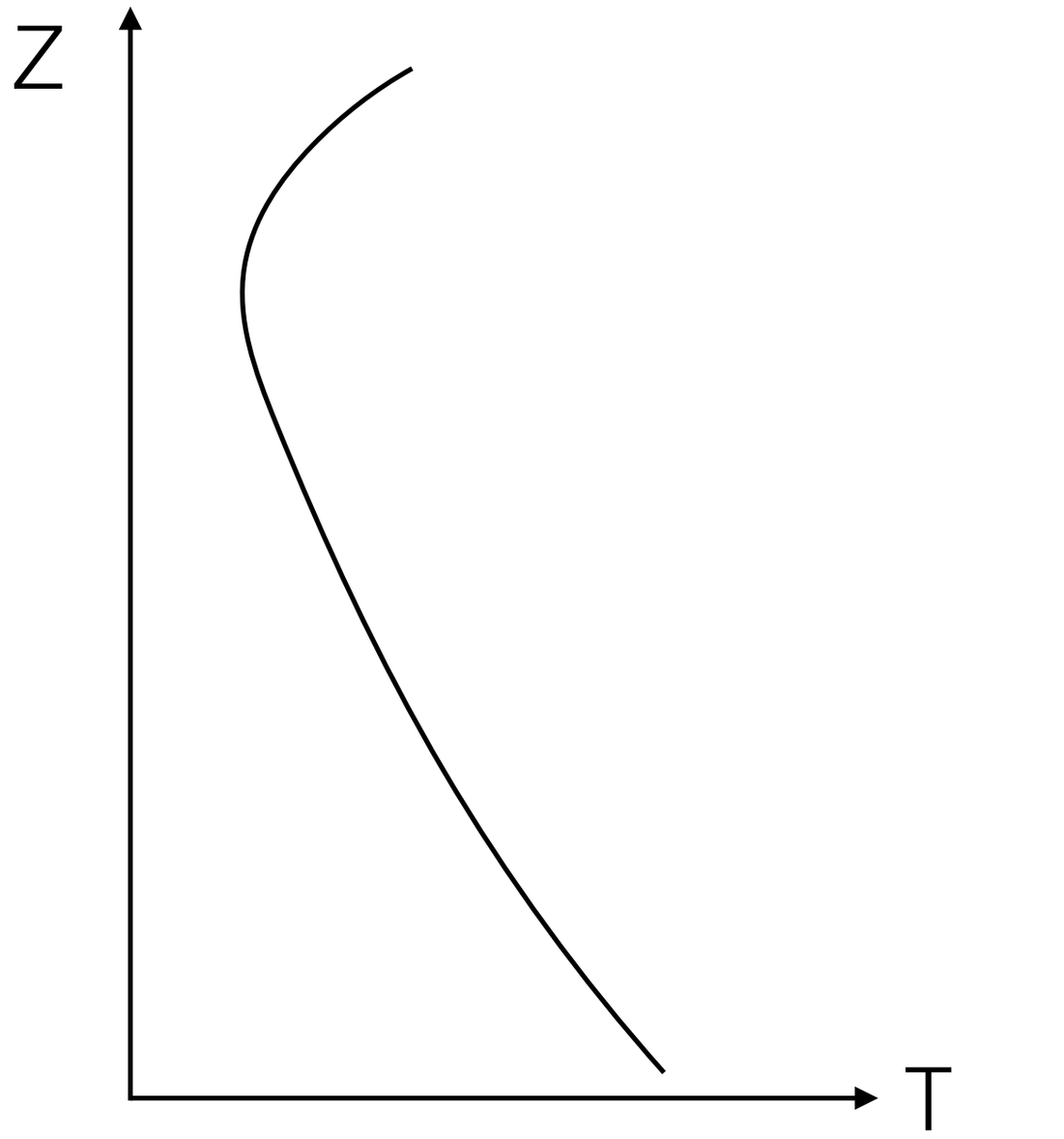

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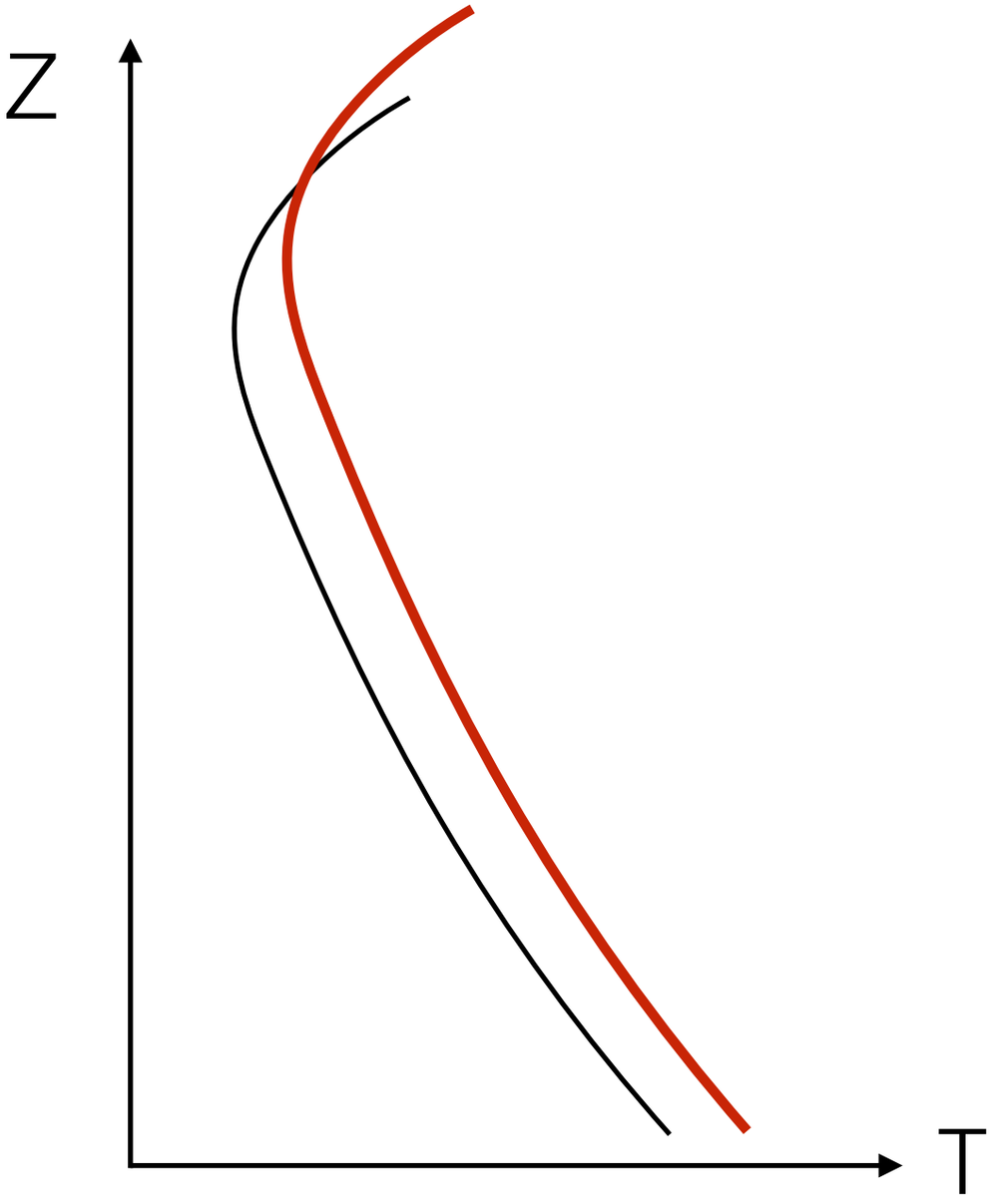

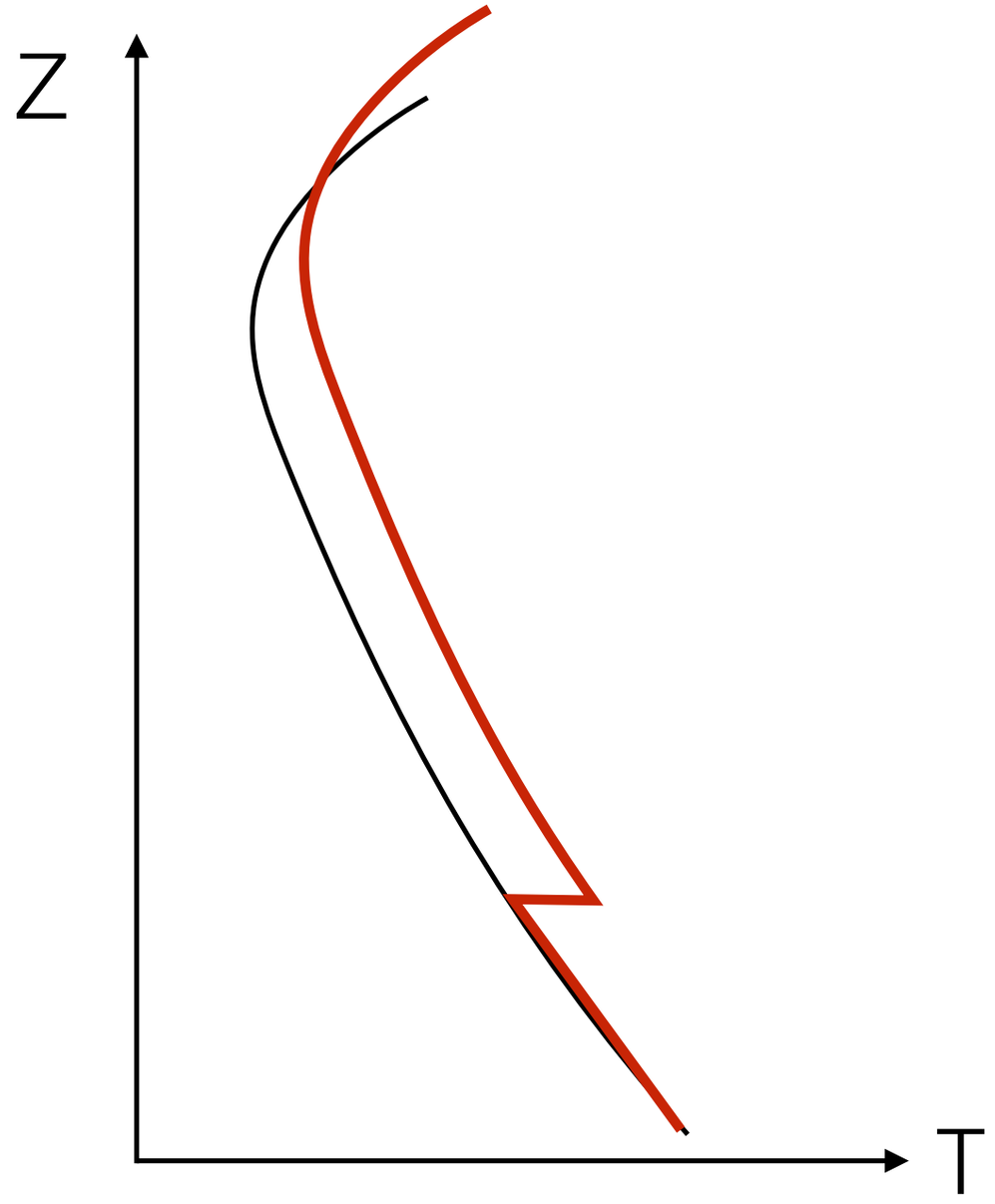

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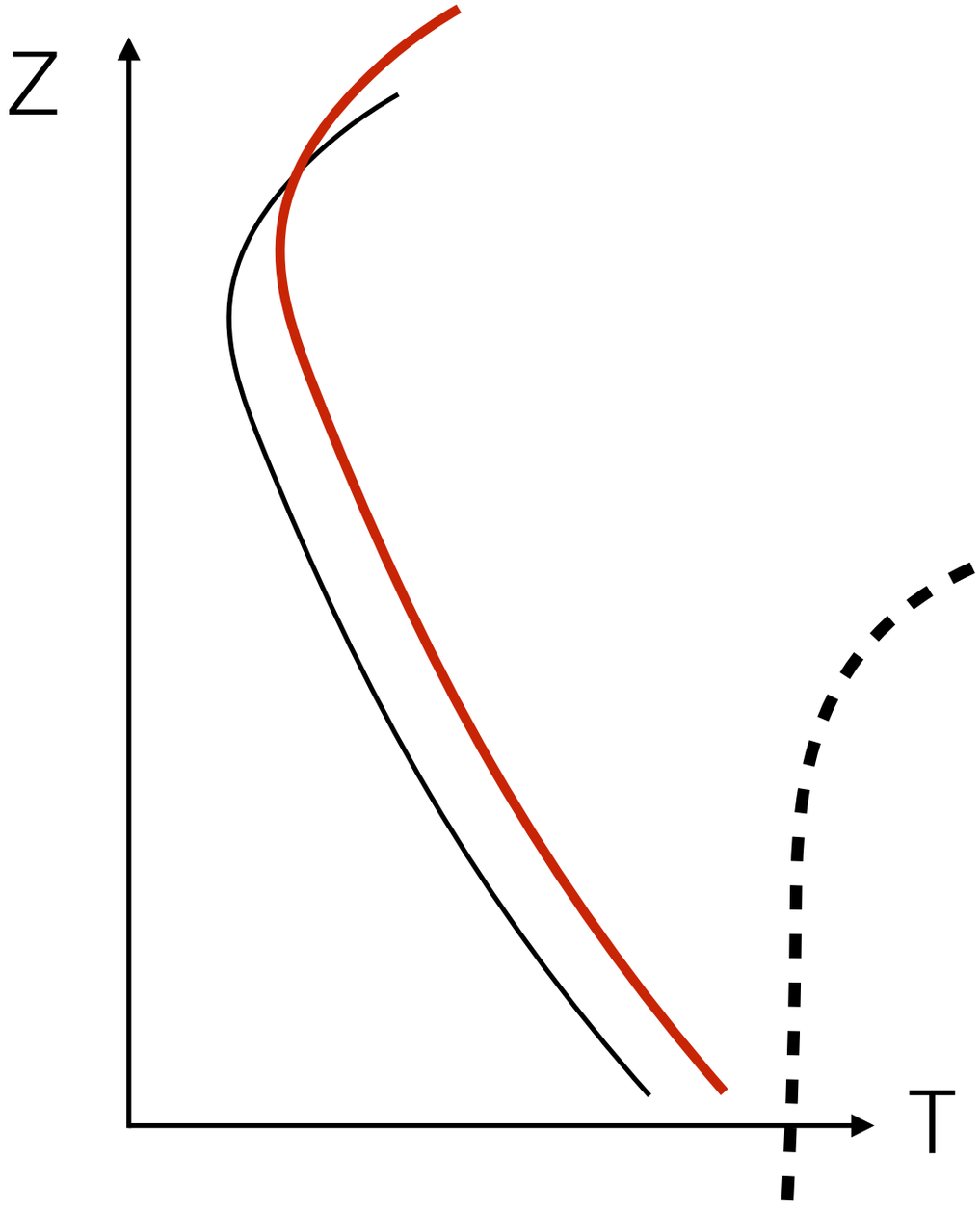

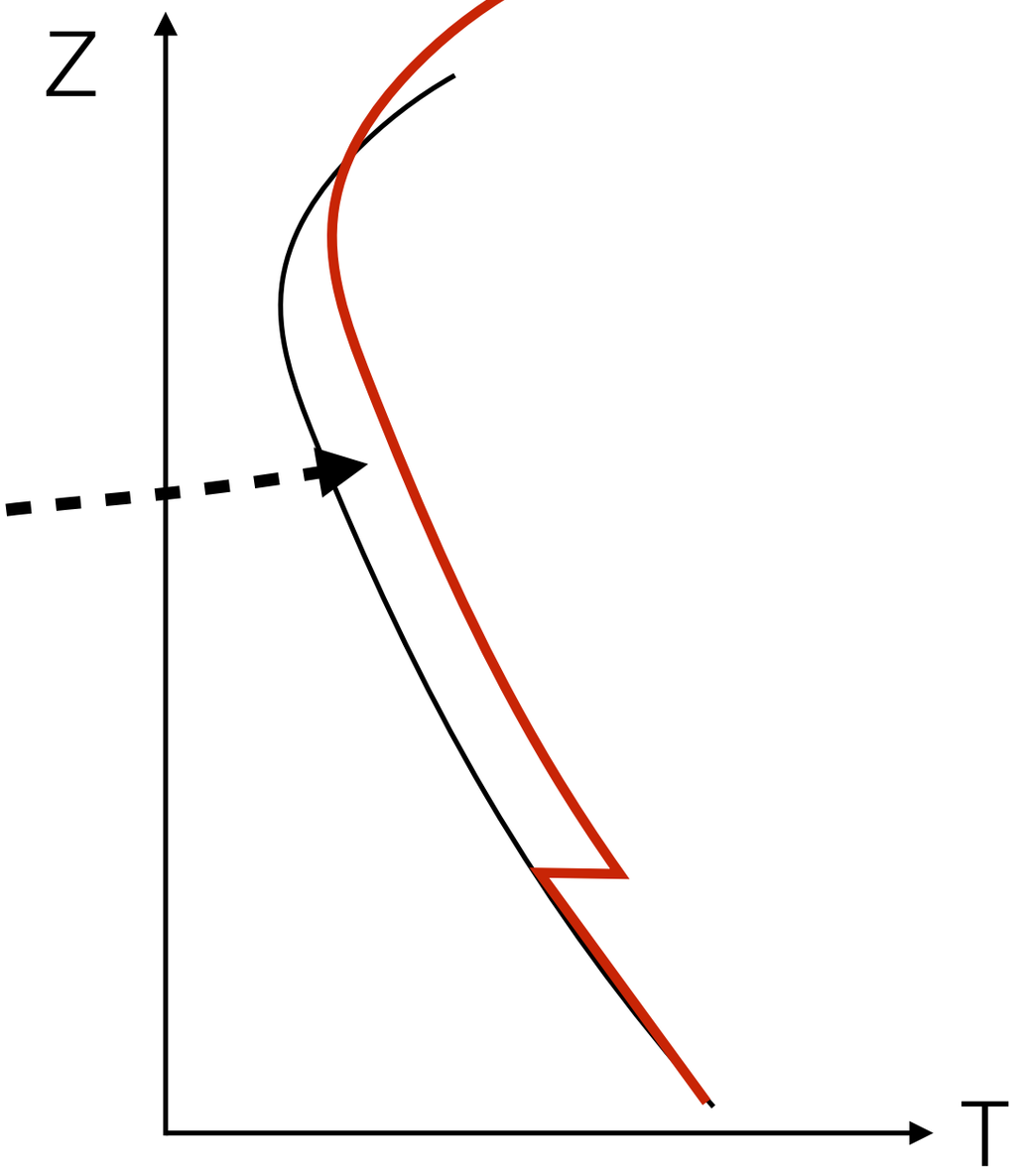

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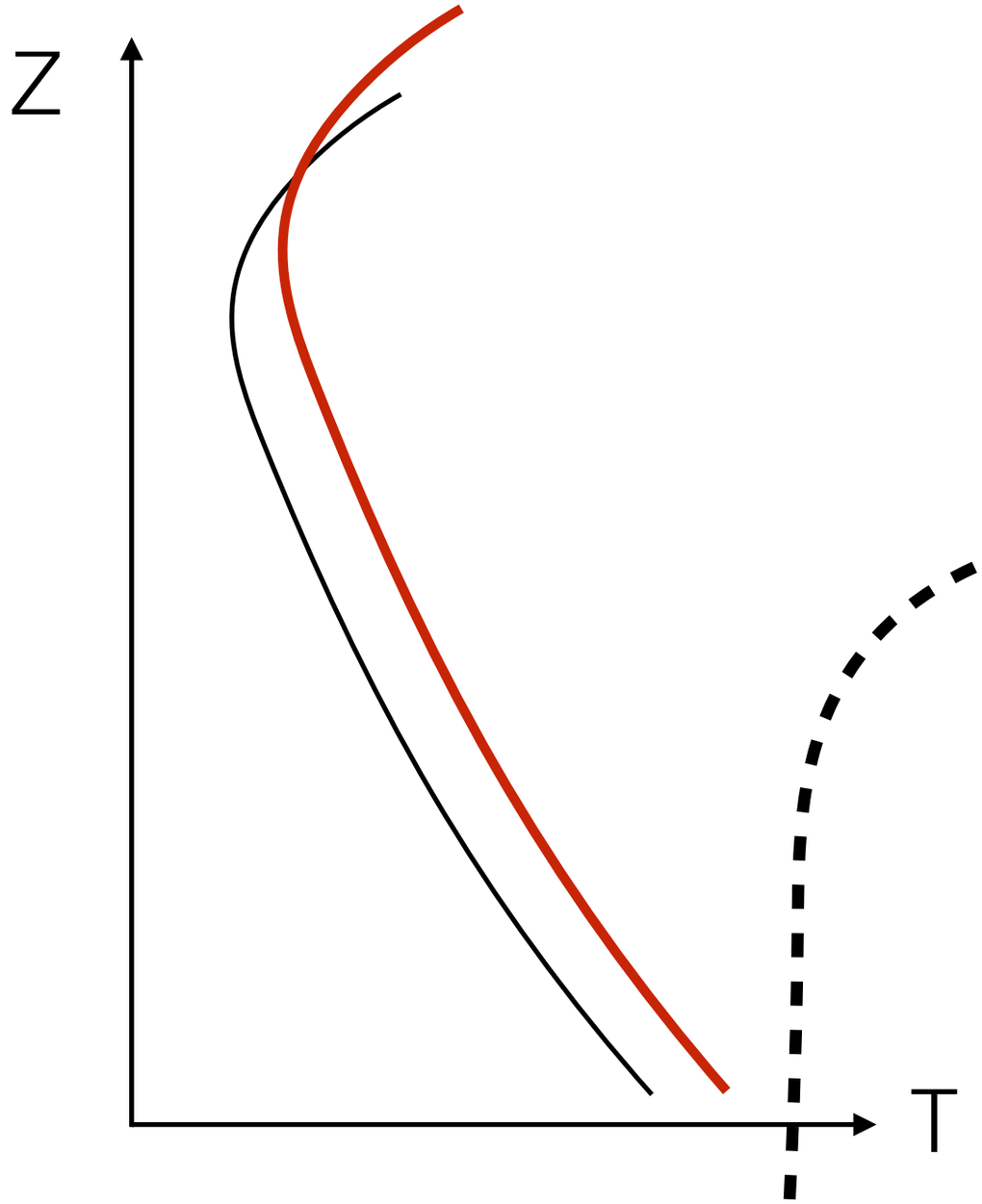

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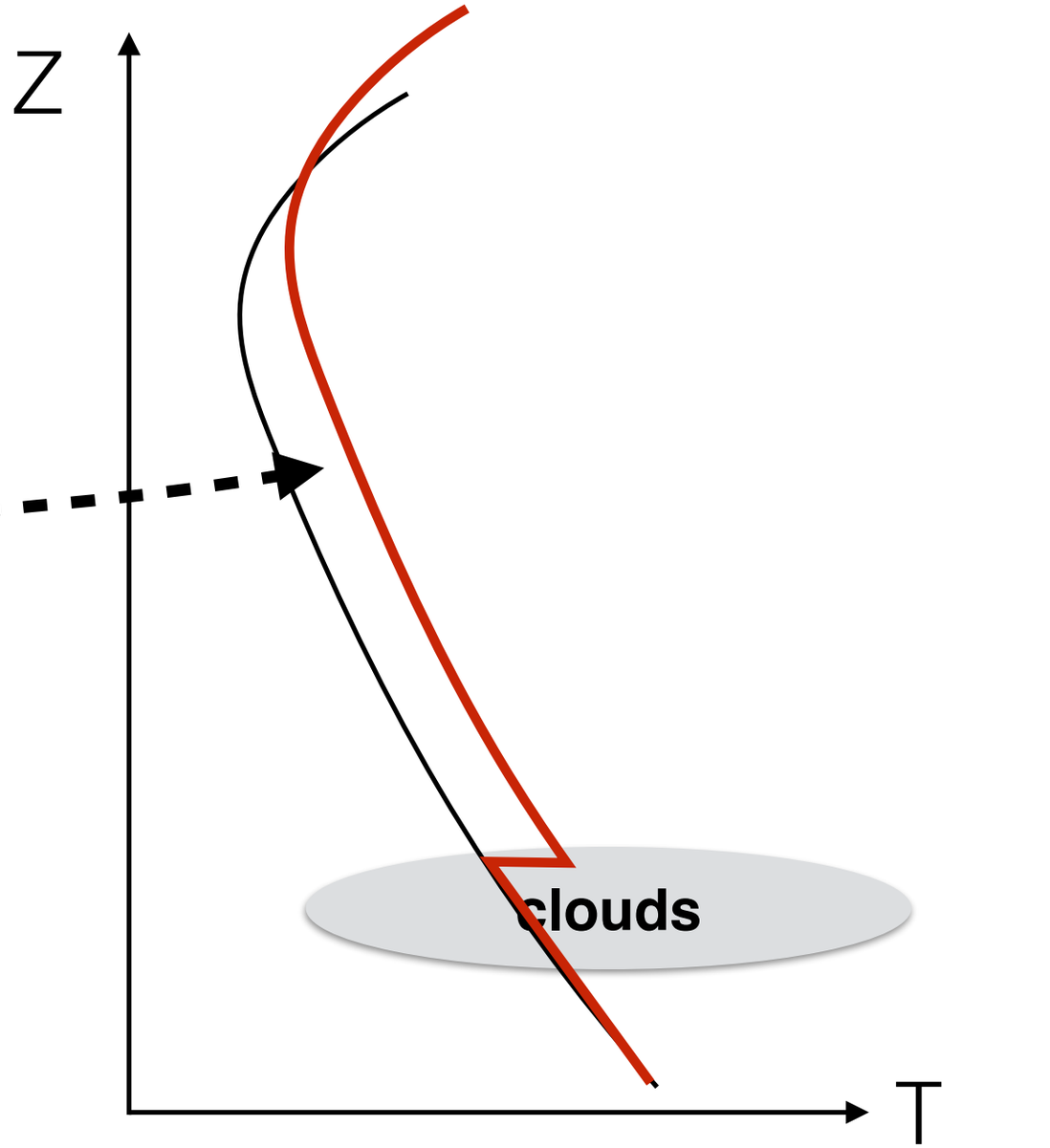

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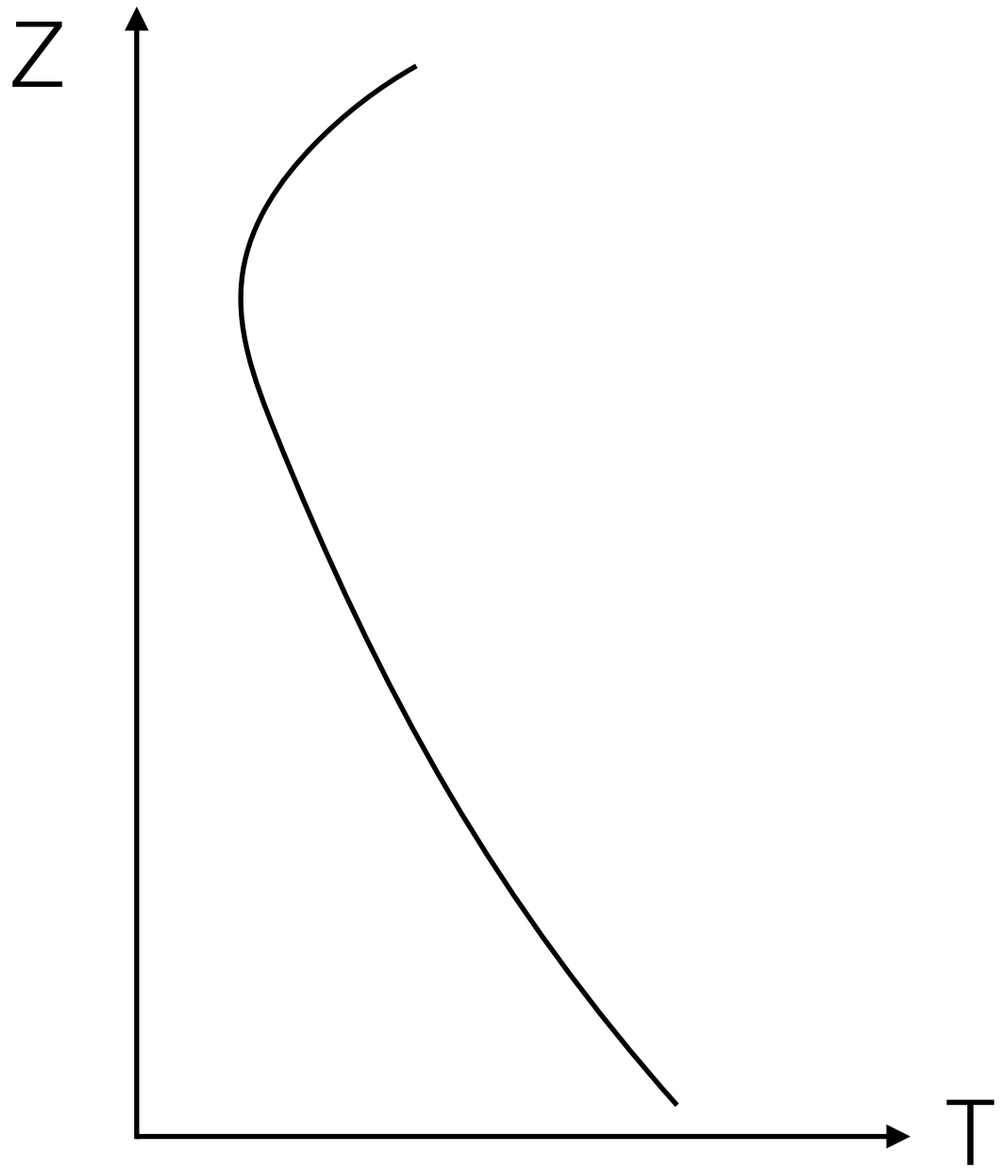

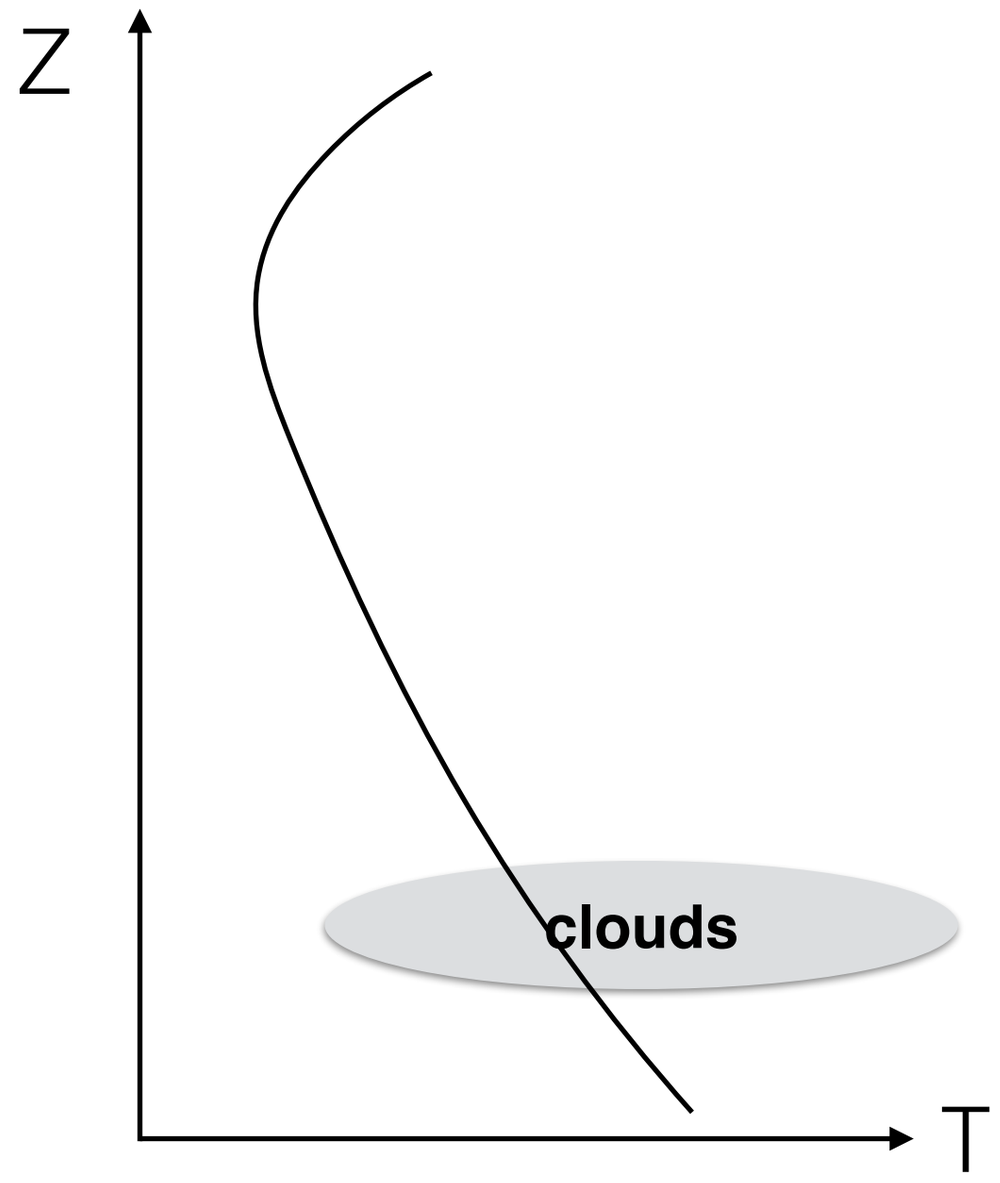

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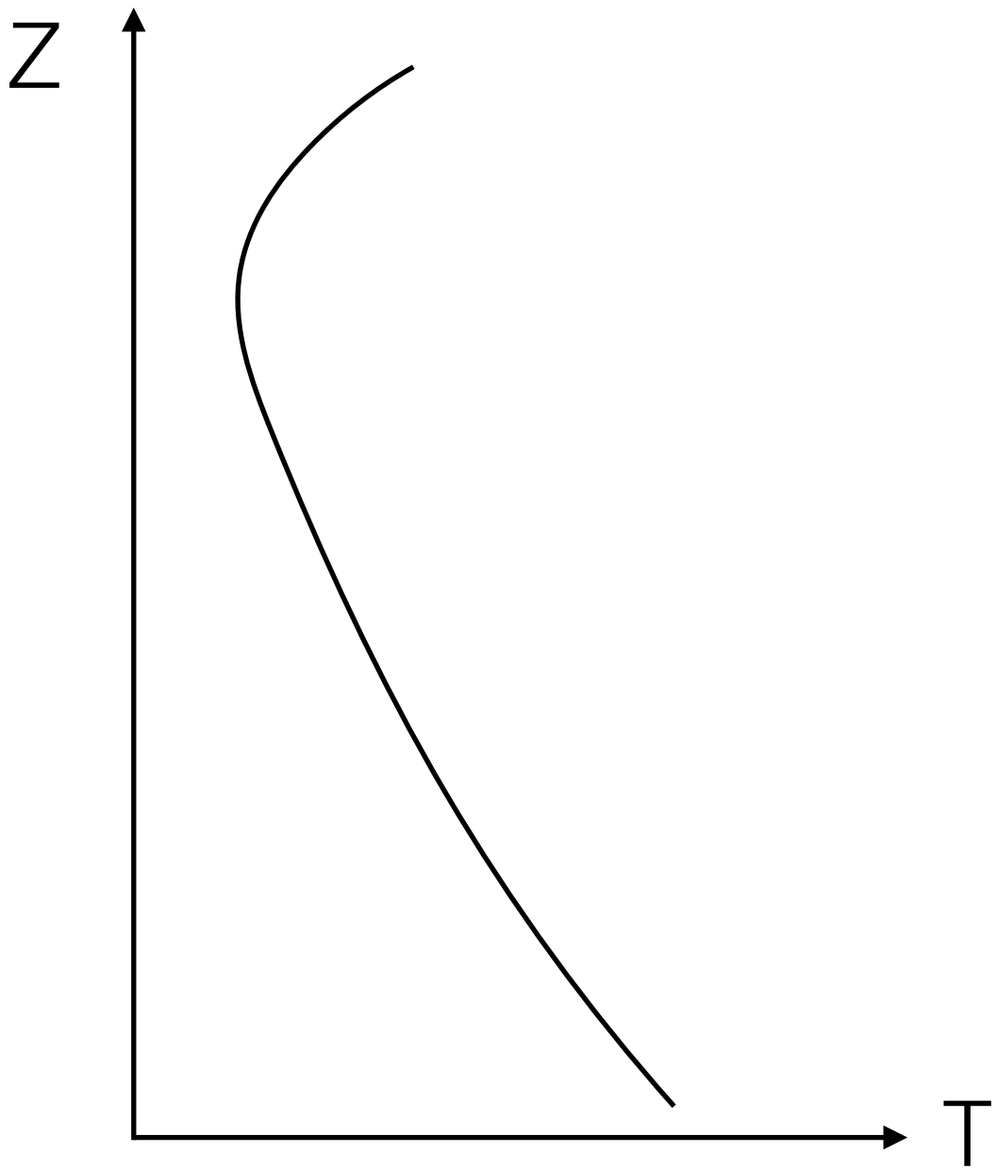

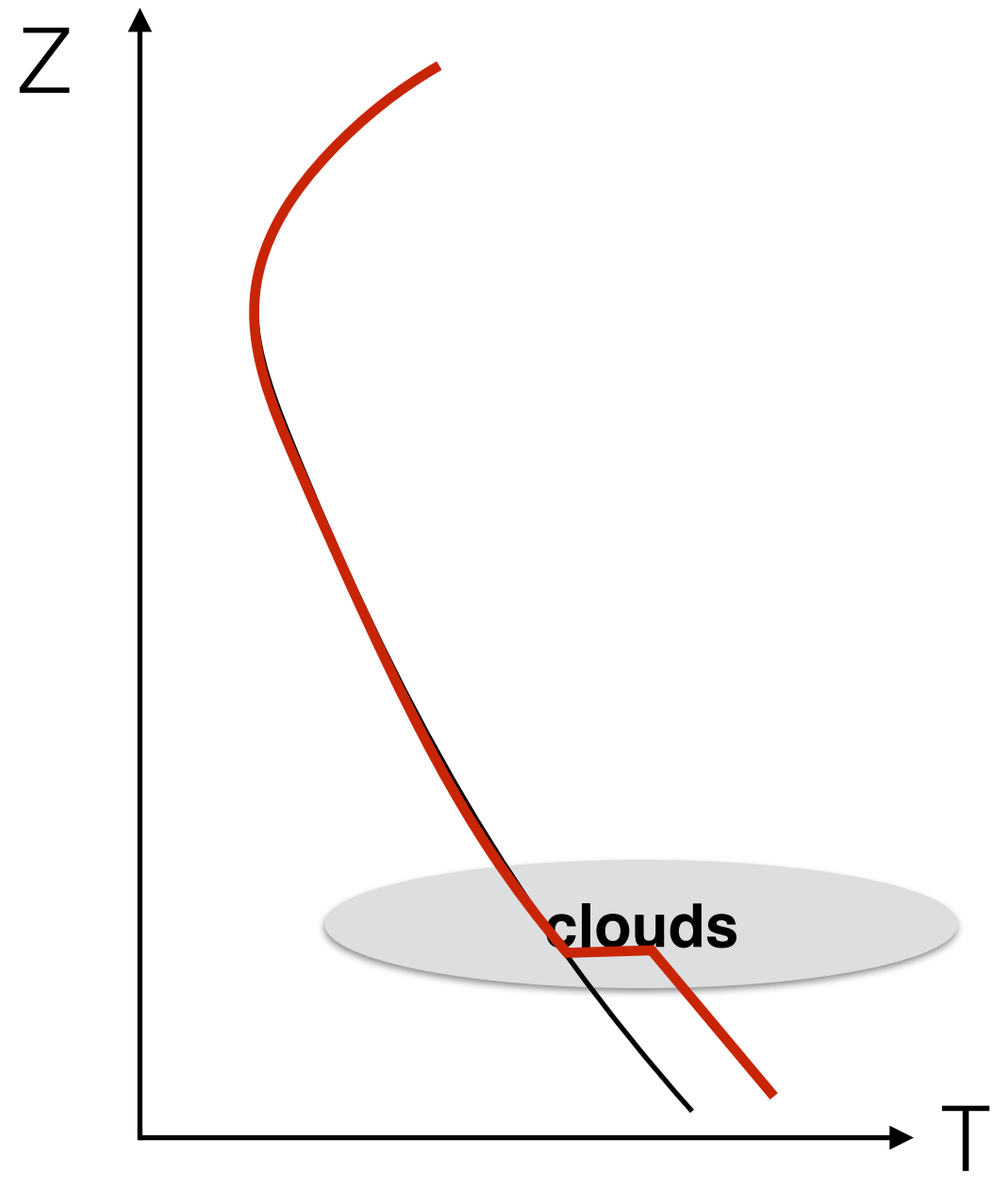

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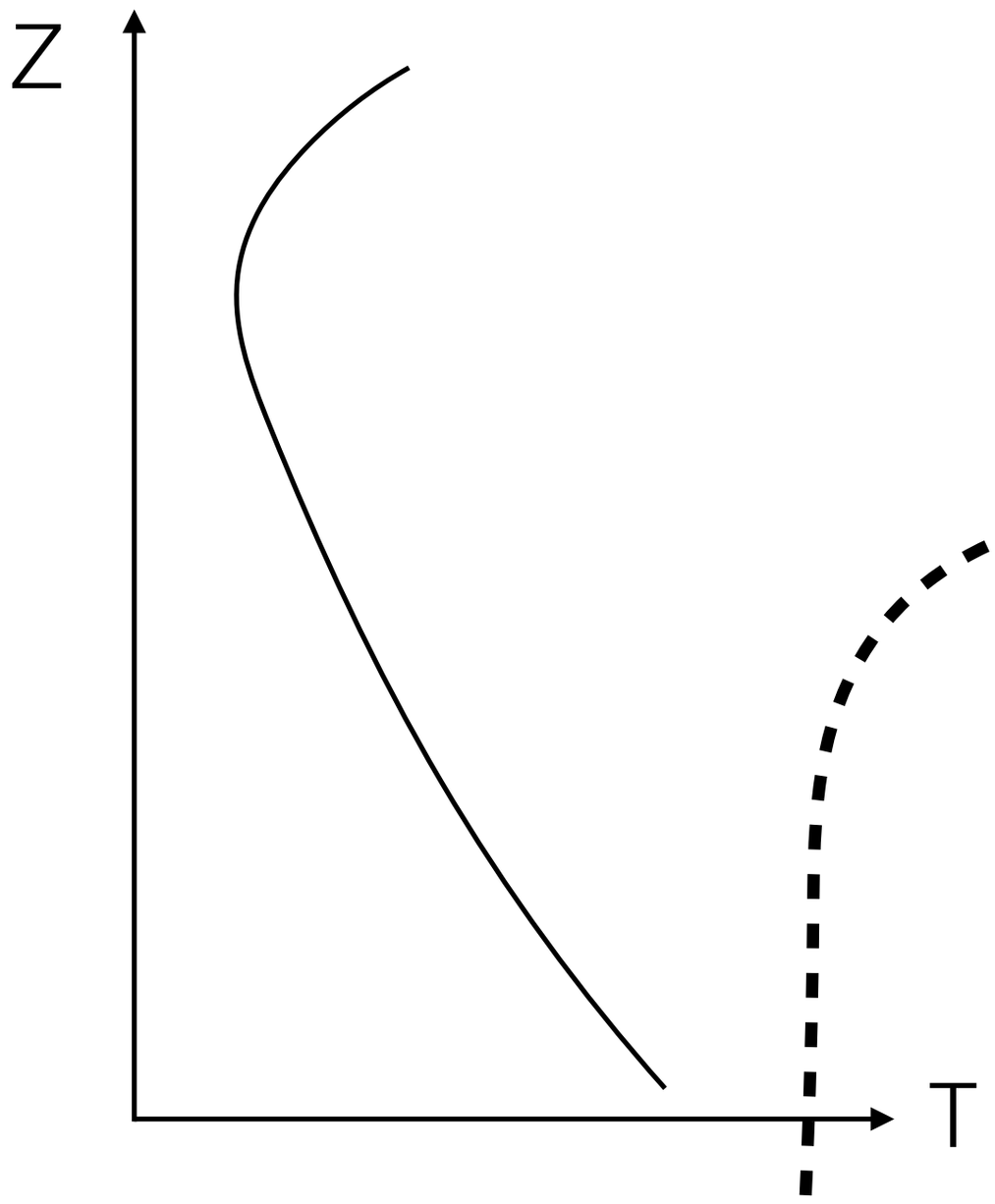

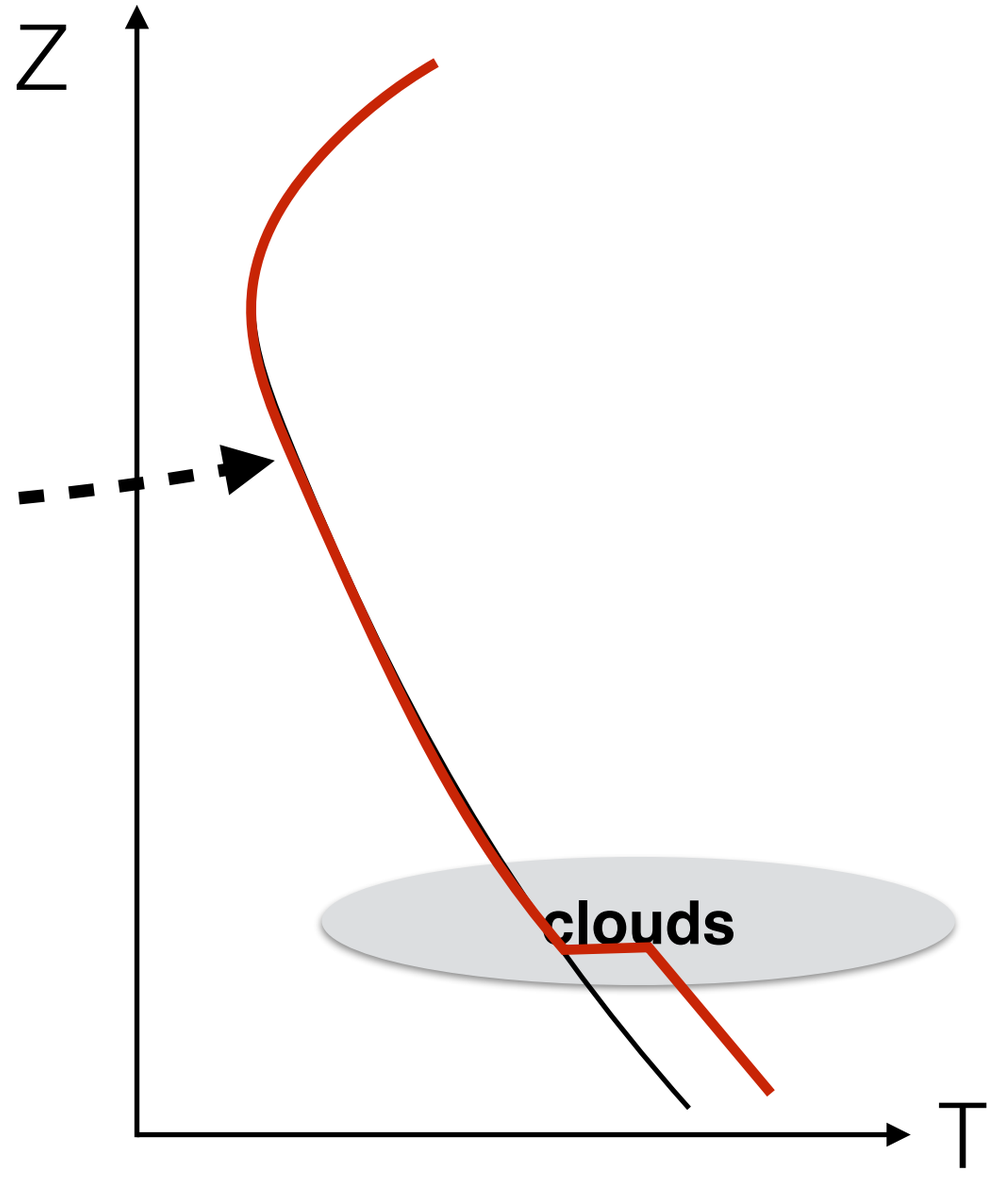

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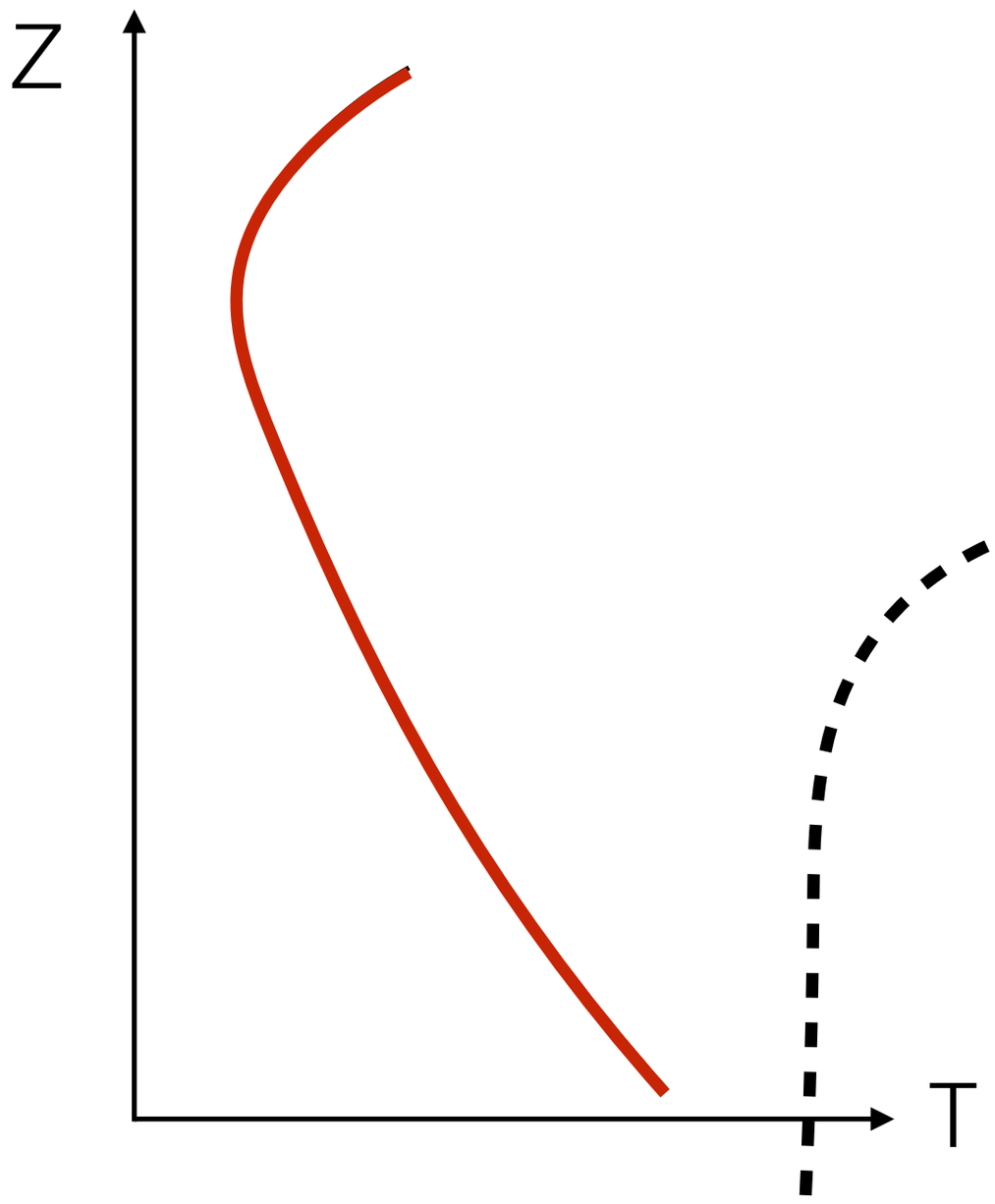

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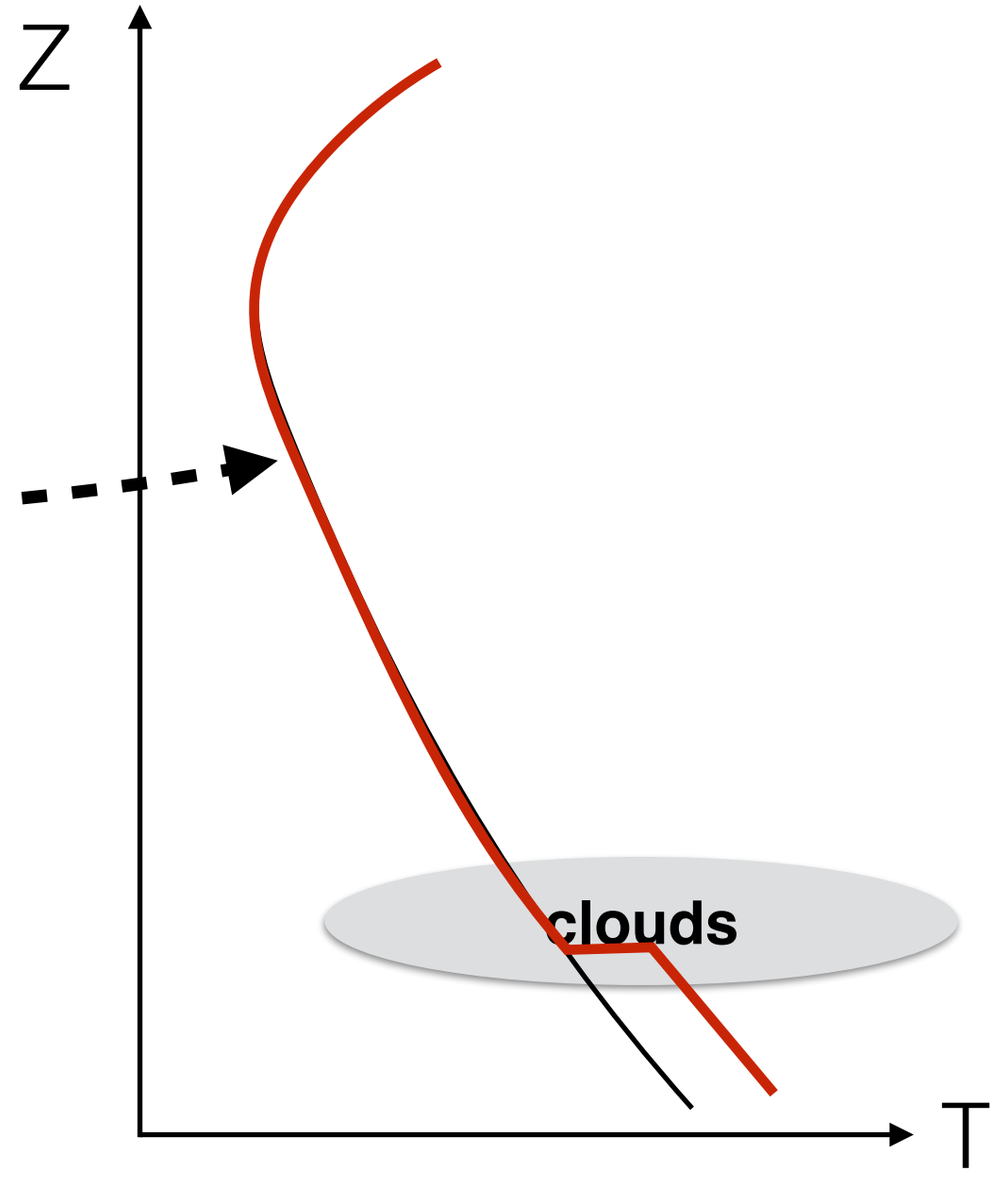

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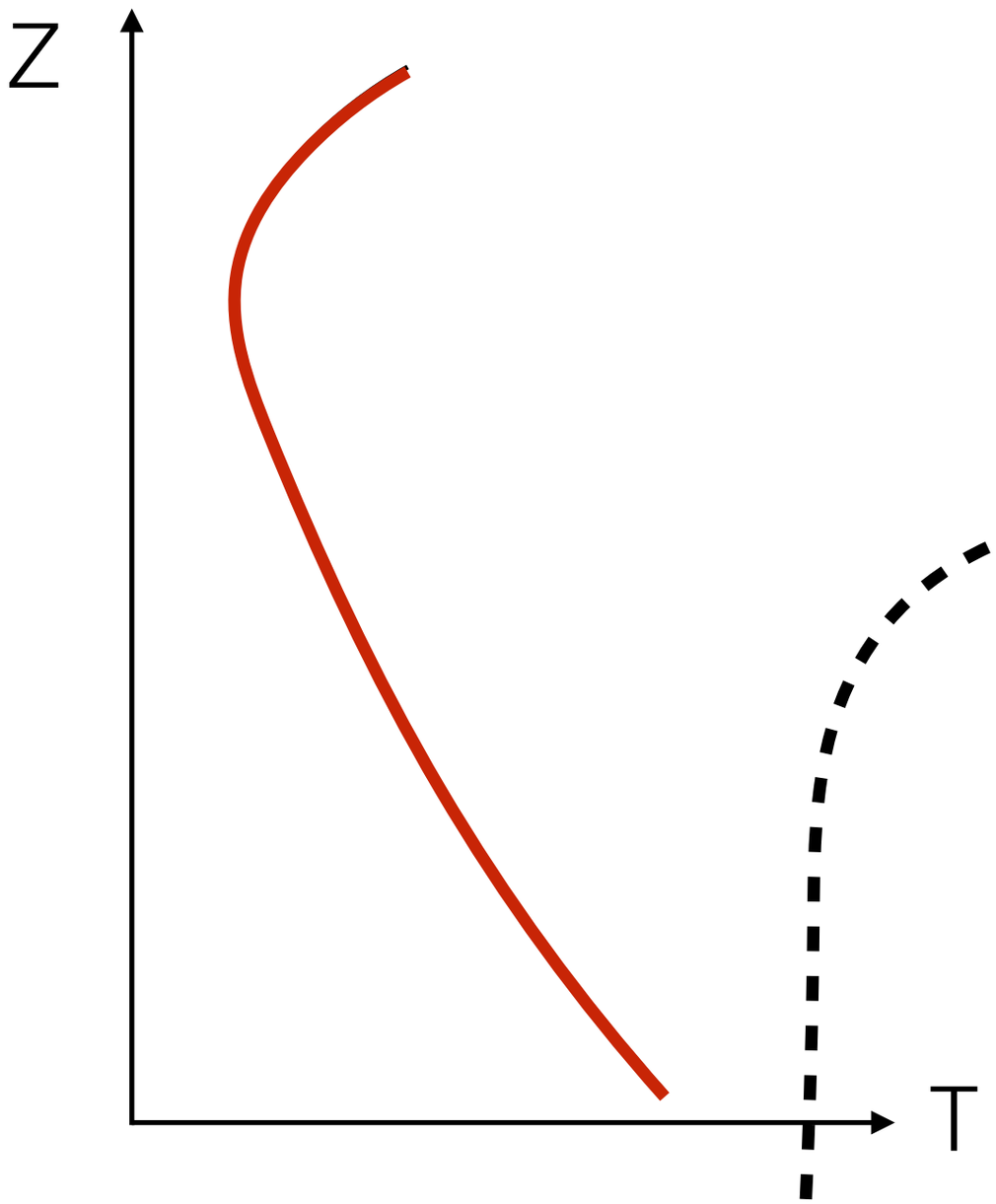

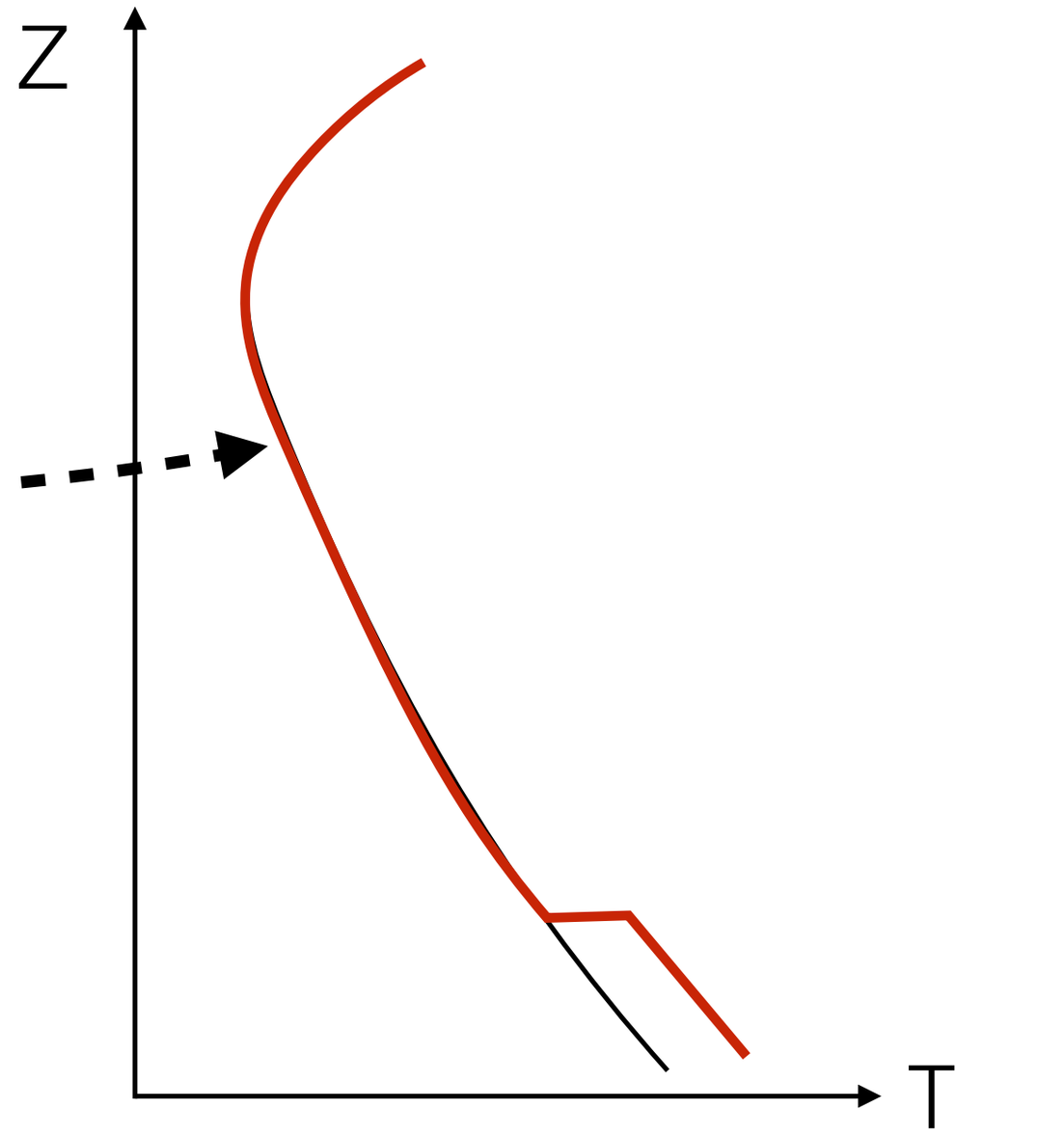

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- heat West Pacific, more low clouds in East Pacific

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- heat West Pacific, more low clouds in East Pacific
- heat East Pacific, less low clouds in East Pacific

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- heat West Pacific, more low clouds in East Pacific
- heat East Pacific, less low clouds in East Pacific
- pattern of warming changes *R*

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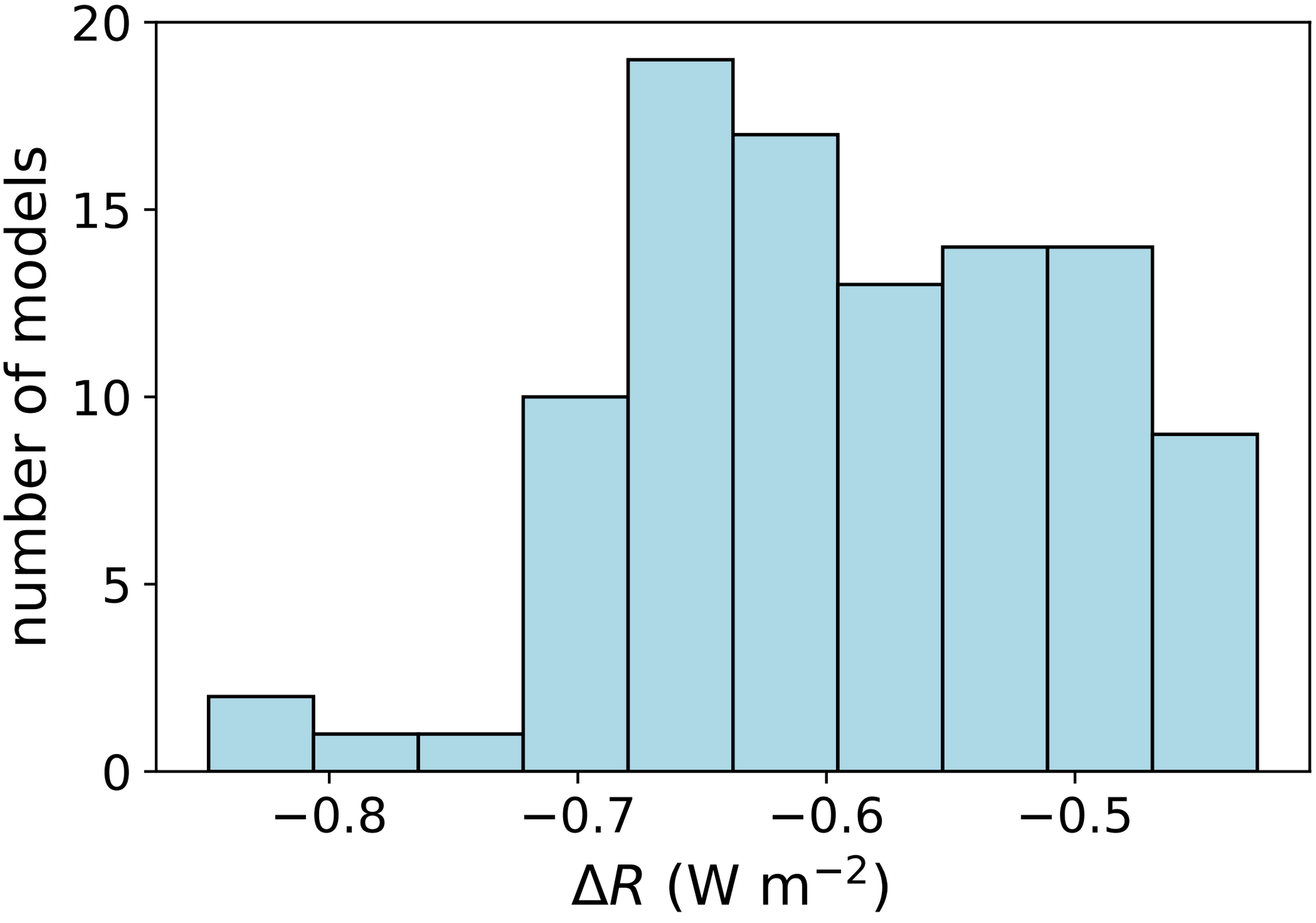

100 runs of MPI-ESM1.1 from 1850-2005

R averaged over 1992-2001

runs identical except for initial conditions

estimating pattern effect

$$R = F + \lambda \Delta T + F_P$$

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AMIP-piForcing

estimating pattern effect

$$R = F + \lambda \Delta T + F_P$$

AMIP-piForcing

- amip-piForcing runs are driven with observed SSTs and sea ice and constant PI atmosphere

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AMIP-piForcing

from 4xCO2 runs

ECS ≈ 3.3 K

- amip-piForcing runs are driven with observed SSTs and sea ice and constant PI atmosphere

estimating pattern effect

$$R = \cancel{F} + \lambda \Delta T + F_P$$

AMIP-piForcing

from 4xCO2 runs
ECS ≈ 3.3 K

observed

- amip-piForcing runs are driven with observed SSTs and sea ice and constant PI atmosphere

estimating pattern effect

$$R = \cancel{F} + \lambda \Delta T + F_P$$

AMIP-piForcing

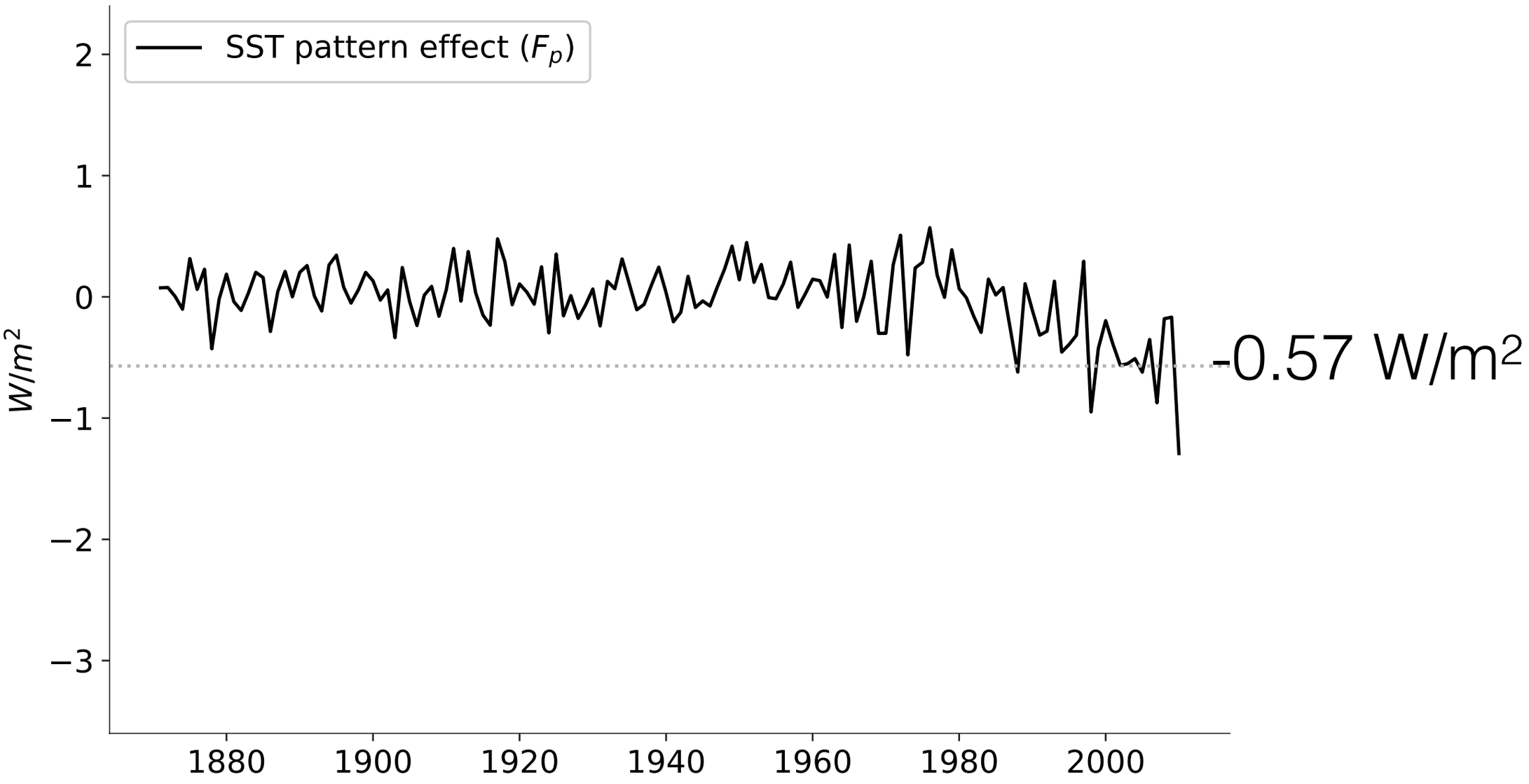
from 4xCO2 runs
ECS ≈ 3.3 K

observed

solve for this

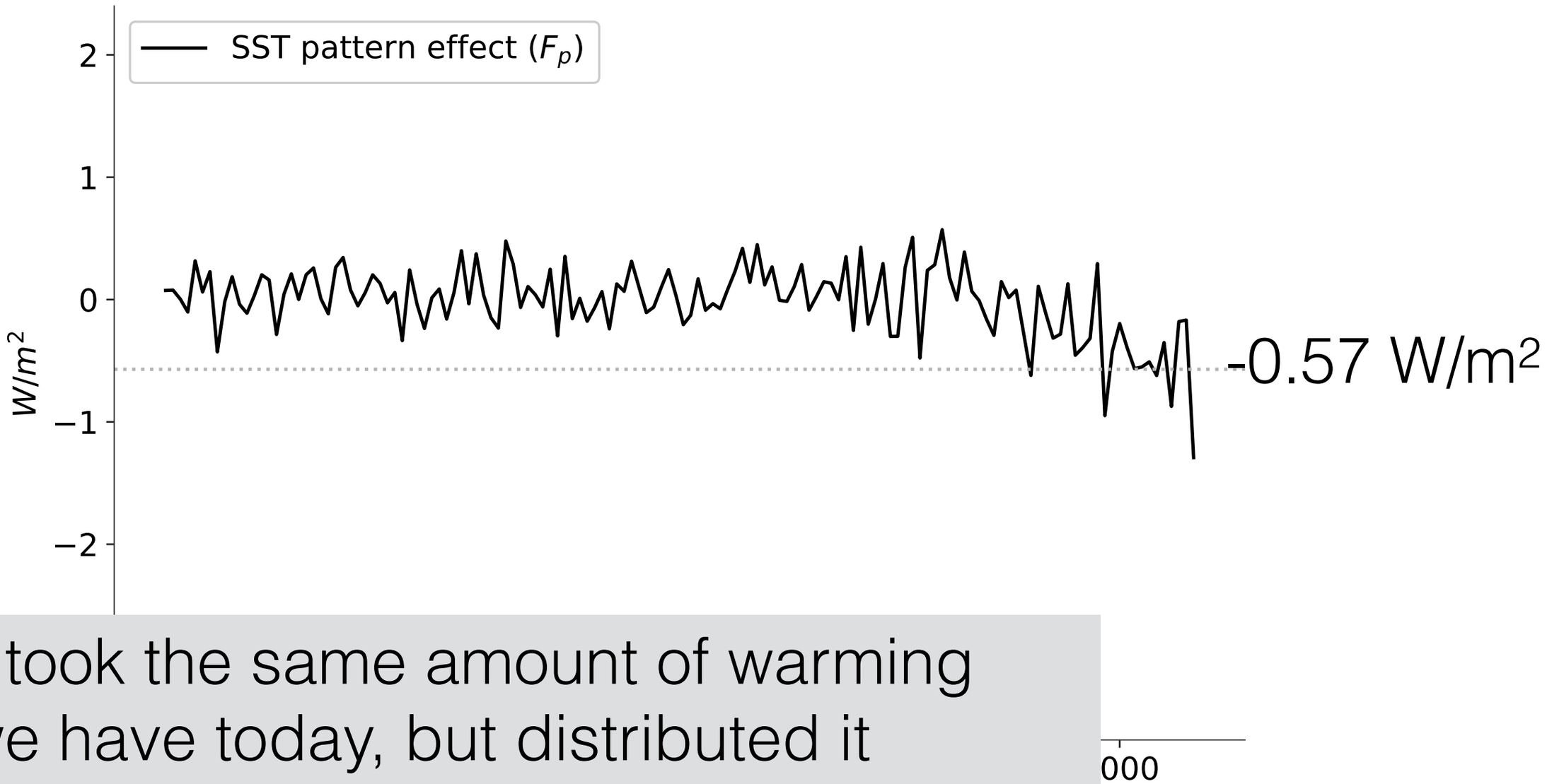
- amip-piForcing runs are driven with observed SSTs and sea ice and constant PI atmosphere

$$R = F + \lambda \Delta T + \boxed{F_P}$$



average of ensemble of 10 models running the same amip-piForcing scenario

$$R = F + \lambda \Delta T + \boxed{F_P}$$



if you took the same amount of warming that we have today, but distributed it following the 4xCO2 equilibrium pattern, then *R* (EEI) would be 1.3 W/m² instead of 0.7 W/m².

$$\boxed{R} = F + \lambda \Delta T + F_P$$

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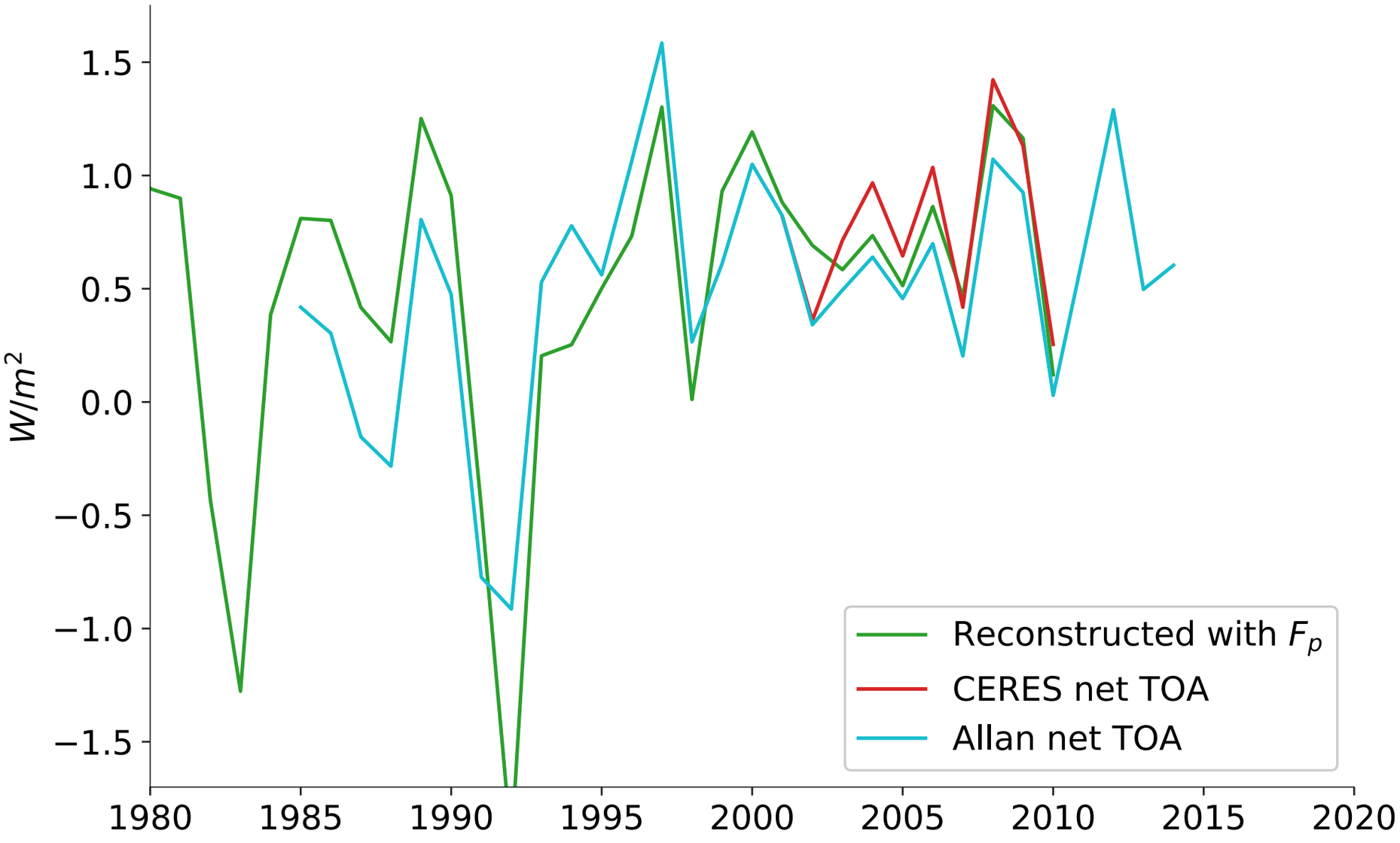
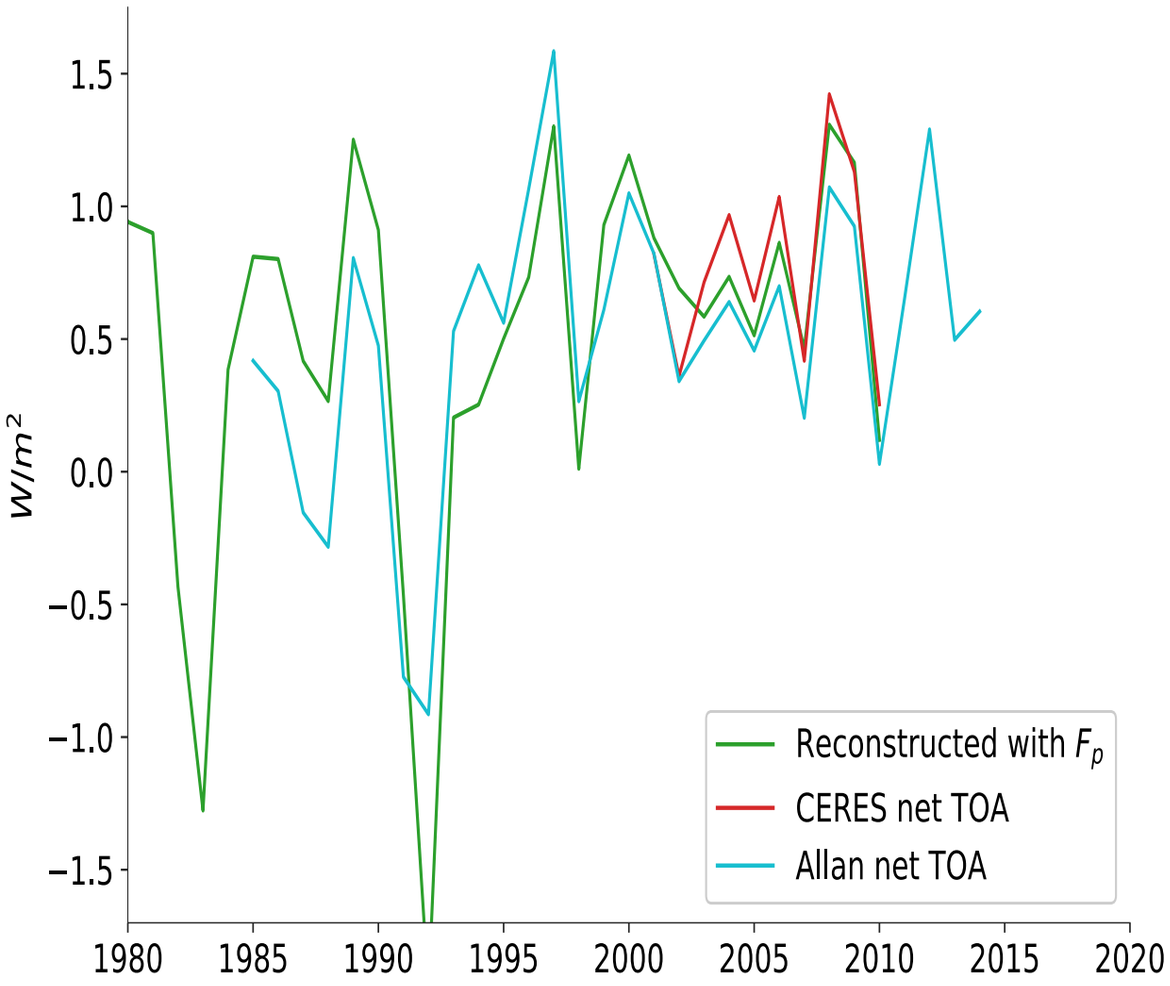
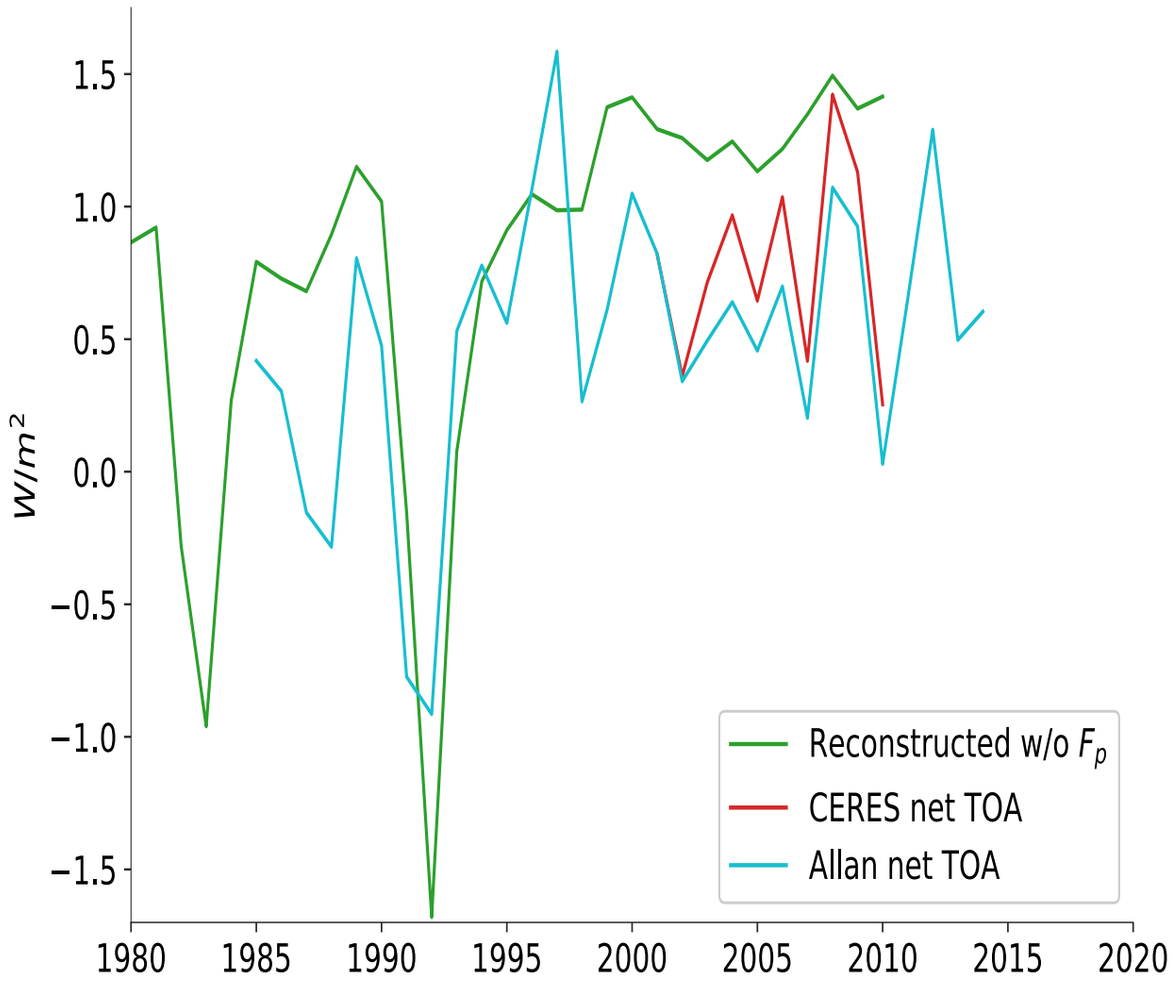


$$\boxed{R} = F + \lambda \Delta T + F_P$$

with pattern effect



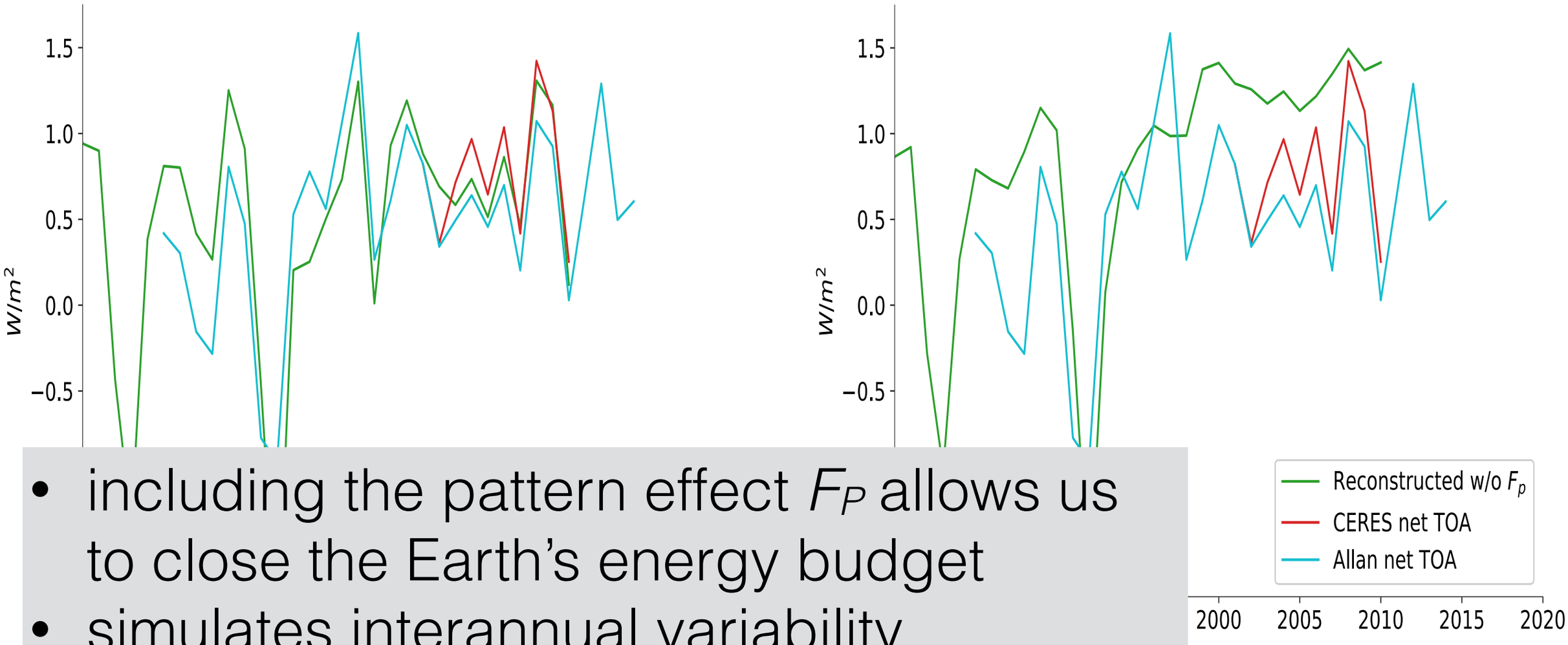
without pattern effect



$$\boxed{R} = F + \lambda \Delta T + F_P$$

with pattern effect

without pattern effect



- including the pattern effect F_P allows us to close the Earth's energy budget
- simulates interannual variability
- level of "consilience" that increases my confidence in mainstream view

committed warming

$$R = F + \lambda \Delta T + F_P$$

at equilibrium

$$R = F + \lambda \Delta T + F_P$$

at equilibrium

$$\cancel{R} = F + \lambda \Delta T + \cancel{F_P}$$

$$0 = F + \lambda \Delta T$$

at equilibrium

$$\cancel{R} = F + \lambda \Delta T + \cancel{F_P}$$

$$0 = F + \lambda \Delta T$$

$$\Delta T = -\frac{F}{\lambda}$$

at equilibrium

$$\cancel{R} = F + \lambda \Delta T + \cancel{F_P}$$

$$0 = F + \lambda \Delta T$$

how much committed warming do we have?

$$\Delta T = -\frac{F}{\lambda} = -\frac{2.4}{-1.14} = 2.1 \,\mathrm{deg\,C}$$

conclusions

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conclusions

- the energy budget for the Earth can be closed by accounting for the pattern effect
- the observed pattern has a magnitude of -0.57 W/m^2, leading to a smaller EEI than if we had the equilibrium warming pattern
- accounting for this, committed warming is > 2°C; likely that staying below Paris limits will require SRM geoengineering
- next big question: we have no theory for F_P